

Evidence Report:

RISK OF INJURY AND COMPROMISED PERFORMANCE DUE TO EVA OPERATIONS

Human Research Program

Human Health and Countermeasures Element

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TABLE OF CONTENTS

I.	PRD RISK TITLE: RISK OF INJURY AND COMPROMISED PERFORMANCE DUE TO EVA OPERATIONS	1
II.	EXECUTIVE SUMMARY	1
III.	INTRODUCTION	1
III.1.	Injury	2
III.2.	Compromised Performance	3
III.2.1.	Integrated Suit Tests.....	3
III.2.2.	Analog Tests & Training.....	4
III.2.3.	Characterization of EVA Research Environments.....	7
IV.	CONTRIBUTING FACTORS	9
IV.1.	Suit Habitability.....	10
IV.1.1.	EVA Suit Design.....	10
IV.1.2.	EVA Suit Fit.....	22
IV.1.3.	EVA Glove Function.....	24
IV.1.4.	Waste Management	26
IV.1.5.	Nutrition and Hydration	26
IV.2.	In-Suit Physical Environment.....	28
IV.2.1.	Hypoxia	28
IV.2.2.	Hypercapnia	29
Internal Suit Pressure		31
IV.2.3.	31
IV.2.4.	Hyper/Hypothermia.....	31
IV.2.5.	Humidity.....	34
IV.2.6.	Excessive Radiation Exposure	35
IV.2.7.	Decompression Sickness	35
IV.2.8.	Ebullism	36
IV.2.9.	Embolism	37
IV.3.	EVA Factors	37
IV.3.1.	Work Efficiency Index	37
IV.3.2.	EVA Task and Timeline Design	38
IV.3.3.	EVA Resources	39
IV.3.4.	EVA Environment.....	40
IV.3.5.	Quality of EVA Procedures	42
IV.3.6.	EVA Training Inadequacy	42
IV.3.7.	EVA Crew Collaboration.....	43
IV.4.	Physical State.....	43
IV.4.1.	Crewmember Physical Preparation	43
IV.4.2.	Pre-Existing Injury or Illness	45
IV.4.3.	Fatigue.....	45
IV.5.	Mental State.....	46
IV.5.1.	Situational Awareness	46
IV.5.2.	Cognitive State	46
IV.5.3.	Psychological State	47
V.	COMPUTER-BASED MODELING AND SIMULATION	47

V.1.	Life Sciences Implications of EVA.....	47
V.1.1.	EVA Timeline Analysis and Computational Modeling.....	48
VI.	RISK IN CONTEXT OF EXPLORATION MISSION OPERATIONAL SCENARIOS	49
VII.	GAPS	51
VIII.	CONCLUSION.....	54
IX.	REFERENCES	54
X.	TEAM	63
XI.	LIST OF ACRONYMS	64
XII.	APPENDIX A: EVA GAPS AND MASTER LOGIC DIAGRAM CONTRIBUTING FACTORS MAPPING.....	66

I. PRD RISK TITLE: RISK OF INJURY AND COMPROMISED PERFORMANCE DUE TO EVA OPERATIONS

Description: Given the high physiological and functional demands of operating in a self-contained EVA or training suit in various gravity fields and system environments, there is a possibility that crew injury can occur and physiological and functional performance may be comprised

II. EXECUTIVE SUMMARY

During future missions to the Moon, asteroids, and Mars, each crewmember will most likely perform up to 24 hours a week of extravehicular activity (EVA) in support of exploration, science, construction, and maintenance tasks. The effectiveness and success of these missions will depend on designing EVA systems and developing operations concepts that maximize human performance and efficiency while minimizing health and safety risks for crewmembers.

Currently, over 400 EVAs have been performed in microgravity using the Extravehicular Mobility Unit (EMU). EMU use during EVA led to the successful assembly of the International Space Station (ISS), and has been essential for other payload experiments, satellite launches and repairs. All of this work was accomplished with crewmembers performing no more than 4 EVAs during a single shuttle mission and without any back-to-back EVAs. However, these successful missions resulted in more injury to EVA crewmembers than may be acceptable for long-duration exploration missions.

The Apollo astronauts completed EVA tasks in suits that were designed for their short-duration lunar missions, although suit mobility problems were evident. The more frequent EVAs and more varied EVA tasks that are anticipated during the future longer-duration exploration missions will require EVA suits and systems that are better oriented to human health and performance than those used during the Apollo Program. Many of the problems that were encountered with the Apollo EVA suits (e.g., limited mobility and dexterity, high and aft center of gravity, and other features requiring significant crew compensation) will need to be corrected or mitigated to optimize EVA objectives of exploration missions.

It is critical that we understand how EVA system design variables such as suit pressure, weight/mass, center-of-gravity location, joint ranges of motion, and biomedical monitoring, affects the ability of astronauts to perform safe, efficient, and effective EVAs. To achieve this understanding, EVA researchers will need to develop and execute an integrated human testing program across multiple environments. The research will provide objective data that will enable informed design decisions and crewmember standards, thereby ensuring EVA systems that optimize crewmember health, safety, efficiency, and performance.

This report describes the risks to crew health, safety, performance, and efficiency caused by EVA operations, and provides the evidence base to substantiate the importance of the risks.

III. INTRODUCTION

Providing the capability for humans to work productively and safely while performing an EVA involves many important contributing factors. Maintaining sufficient total pressure and

oxygen partial pressure in the EVA suit is vital not only to human health, but also to survival. Efficient prebreathe protocols must adequately reduce the amount of inert gas in astronauts' blood and tissues to prevent decompression sickness (DCS) at hypobaric suit pressures. The EVA suit must be ventilated to remove expired carbon dioxide (CO₂), both perspired and respired water vapor, and metabolically generated heat. Since ventilation flow alone may not be sufficient to control core body temperature and prevent unwanted heat storage, cooling water is typically circulated through small tubes that are located in garments worn close to the skin. Heat influx also must be controlled, and the EVA crewmember must be protected from harmful space radiation environment. During long duration EVAs, nourishment and water must be available, and accommodations must be provided for liquid and solid waste collection.

Considerable evidence shows that inadequate design of any aspect of an EVA suit system can have serious consequences. A large body of evidence in this area is derived from astronauts' first-hand experience and non-experimental observations (e.g., Category III and Category IV). Evidence has also been gathered in a rigorous, controlled manner during which subjects served as their own controls from shirt-sleeved to suited conditions, and across repeated measures trials in which a single parameter is varied (e.g., Category II). This report identifies and describes the various risks, contributing factors, and associated evidence for injury and compromised performance due to EVA operations.

III.1. Injury

Gas pressurized spacesuits have been shown to cause injuries and increase metabolic expenditure (Longnecker et al. 2004; Maida et al. 1996; Williams and Johnson 2003b)(Carr 2005; Jones et al. 2008; Viegas et al. 2004) (Opperman et al. 2010b; Scheuring et al. 2009). After performing his first spacewalk, Alexi Leonov was nearly unable to reenter the spacecraft because his suit was immobile and he was unable to see through his fogged visor. Apollo astronauts sustained hand, joint, and skin irritation injuries (Scheuring et al. 2008).

The current U.S. spacesuit, the EMU, causes a variety of musculoskeletal injuries. The EMU is pressurized to 4.3 psi (29.6 kPa), forcing the astronaut to expend energy to deform the suit, and limiting his or her mobility (Maida et al. 1996) (Newman et al. 2000) (Jaramillo et al. 2008; Norcross et al. 2010b; Norcross et al. 2010d; Schmidt et al. 2001). EVA injuries can be divided in two different groups: contact injuries and strain injuries.

Contact injuries refer to contusions, abrasions, or hard impacts with the spacesuit, whereas strain injuries are due to overuse, repeated movements, and development of high muscle forces. Strain injuries can occur when astronauts are manipulating heavy tools, working at the limit of their work envelope, or forcing the shoulder joint against the spacesuit (Strauss 2004).

Hand and finger injuries are the most common injuries during both training and flight, and include onycholysis, fingernail delamination, blisters, contusions, and abrasions (Strauss 2004; Viegas et al. 2004) (Jones 2004; Opperman et al. 2010b; Scheuring et al. 2009). Preventing hand injury is one of the most difficult challenges spacesuit designers face. Shoulder injuries typically occur during training and induce some of the most serious harm. Shoulder injuries have been extensively described by Williams and Johnson (Williams and Johnson 2003b), and continue to be actively researched (Laughlin et al. 2014; Murray et al. 2014). Most injuries occur at the limb

joints (wrist, arms, knees, and ankles) are abrasions and contusions as a result of rubbing and impact against the soft suit components to move the garment.

Although more injuries occur during EVA than elsewhere on-orbit, most injuries have been minor and did not affect mission success (Opperman et al. 2010b; Scheuring et al. 2009; Viegas et al. 2004). However, the number of EVA-associated injuries increased during the many EVAs and training sessions for the construction of the ISS that were conducted in the neutral buoyancy lab (NBL) training pool (Gernhardt et al. 2009). The NBL makes astronauts and tools neutrally buoyant to simulate the weightlessness of microgravity, allowing realistic mission preparation with mockups of the ISS, robotic arms, and other pieces of space hardware. Many hours of training are required for each EVA, and the injuries seen on orbit are increased as more time is spent inside the suit. Also, gravity shifting inside the suit during testing causes new injuries not seen in flight. Shoulder injuries are one of the most severe problems because some training procedures cause the weight of the body to rest on the shoulders, and this type of injury can even require surgical intervention (Opperman et al. 2009; Strauss 2004; Strauss et al. 2005; Williams and Johnson 2003b).

III.2. Compromised Performance

Anyone who has ever spent time inside a pressurized spacesuit understands that their ability to perform tasks is compromised. EVA crewmembers must first be positioned into a spacesuit and then sizing adjustments are made as they learn to move within the constraints of the suit. As compared to 1G shirt-sleeve performance, it takes greater metabolic effort and time to complete even the simplest of tasks in a spacesuit. A spacesuit is a closed system, so when crewmembers hurry to complete tasks they run the risk of overexertion, overheating, fatigue, and frustration. Currently, human performance constraints during EVA are managed operationally through extensive EVA training in the NBL prior to flight, but this experience is limited to the EMU, microgravity, metabolic data collection and operational training paradigms. Detailed discussion of the factors that contribute to compromised performance will be covered in Section IV, Contributing Factors.

To expand and improve collection of human performance data during EVA, the EVA Physiology, Systems, & Performance (EPSP) Project used lunar environment analogs (such as parabolic flight aircraft, NASA Extreme Environment Mission Operations [NEEMO], NBL, remote field test sites, and JSC's Partial Gravity Simulator [POGO] in the Space Vehicle Mock-up Facility) to characterize human performance and suit-human interactions during partial-gravity EVA. The project worked with the Constellation EVA Systems Project Office (ESPO) to develop and execute an integrated human testing program across multiple analogs. Along with the EPSP/ESPO tests that provided objective human performance data, the Exploration Analogs and Mission Development (EAMD) team worked to evaluate EVA operational concepts that were based on the lunar surface scenarios. The results from these efforts were integrated to enable informed design decisions, thereby ensuring a surface EVA system that optimizes crewmember health, safety, efficiency, and performance.

III.2.1. Integrated Suit Tests

EPSP and ESPO initiated a series of tests, collectively referred to as the Integrated Suit Tests (IST), in January 2006 with the EVA Walkback Test (EWT). Following the EWT, Integrated Suit Test 1 (IST-1), Integrated Suit Test 2 (IST-2), Integrated Suit Test 3 (IST-3), and the

Integrated Parabolic Flight Test took place. EWT, IST-1, IST-2, and IST-3 were performed on POGO, a simulator in the Space Vehicle Mockup Facility that utilizes a pneumatic system to offload the weight of suited and unsuited subjects to produce partial gravity. The Integrated Parabolic Flight Test utilized the C-9 parabolic flight aircraft provided by the Reduced Gravity Office.

In the EWT, the feasibility of a suited 10-km ambulation was tested to represent a case in which a rover breaks down on the lunar surface and a crew is forced to walk back to their habitat or ascent vehicle. The EWT was also performed to determine physiological and biomechanical suit parameters (Norcross et al. 2009). The IST-1 objective was to identify the effects of weight, inertial mass, pressure, and suit kinematics on the metabolic cost of ambulation in a spacesuit, specifically in the MK-III spacesuit technology demonstrator, which has a number of features that are expected in future spacesuit designs (Norcross et al. 2010d). Identifying these effects enabled development of predictive models of metabolic rate, subjective ratings, and suit kinematics based on measurable suit, task, and subject parameters. Similar to IST-1, an objective of IST-2 was to establish the metabolic cost associated with changes in weight, inertial mass, pressure, and suit kinematics while performing exploration tasks such as shoveling, rock pickup, kneel-and-recover, and light construction tasks. The additional data furthered the development of the predictive algorithms initiated by IST-1 (Norcross et al. 2010b; Norcross et al. 2010d). Whereas EWT, IST-1, and IST-2, each included unsuited and suited tests, IST-3 contained only an unsuited component because of POGO lift capacity limitations. For IST-3, the direction shifted toward exploring the effects of changes in center of gravity on human performance including metabolic rate, biomechanics, and subjective measures (Norcross et al. 2010c). The Integrated Parabolic Flight Test used the superior partial gravity environment of the C-9 aircraft to determine the separate effects of changes in suited weight and mass as well as suited center of gravity (Chappell et al. 2010a).

The data gathered from the Integrated Suit Tests have assisted in determining how typical EVA work correlates with exercise. Once the metabolic rates, biomechanics, and subjective measures during EVA-like activities (such as walking and shoveling) are quantified, exercise protocols that work to supplement the exercise achieved during EVA can be developed for long-duration missions.

III.2.2. Analog Tests & Training

III.2.2.1. NBL

As part of the astronaut mission training sequence, a crewmember will spend approximately 7 to 10 hours training for every hour of an EVA, depending on the difficulty of the EVA. Training takes place at the Sonny Carter Training Facility's NBL. Training is performed in the 202 ft. long, 102 ft. wide, 40 ft deep pool, which contains mockups of the International Space Station. The suited astronauts are made neutrally buoyant with the strategic placement of weights to simulate the weightlessness encountered in space.

During the EVA simulation, measurements of the gas flow-rate through the spacesuit (supply and return) are obtained through a digital connection to a flow meter and computer located on the Environmental Control System (ECS) panel. The concentration of expired CO₂ is captured from gas samples taken at the end of the return umbilical that vents out the expired gas mixture. The

two samples are fed into a laptop computer running a LabView program specifically designed for this purpose. A series of calculations use the supply flow-rate and CO₂ measurements to determine the volume of oxygen consumed (VO₂) and the volume of carbon dioxide (VCO₂) produced. A linear combination of the VO₂ and VCO₂ in the Weir equation is used to determine the metabolic rate (met rate) once every second for the duration of the simulation (Klein et al. 2008).

The test conductor supplies a timeline of the simulation, which is used to break the data into individual tasks. The duration of each task, along with the minimum, maximum, and average metabolic rate and the change in tank pressure are all calculated and recorded in a task analysis chart. During the training sequence, the EVA trainers and suit engineers use the data to verify the workload of the tasks and consumable consumption; this assists in planning the EVA task sequence to reduce crewmember fatigue and ensure adequate consumables are available. Flight surgeons and biomedical engineers review the data prior to an EVA and use the data when monitoring an EVA. If the met rates during the EVA are higher than those recorded at the NBL, flight surgeons can query crewmembers and determine whether they are having problems with the current task. During an EVA, met rates are calculated from the pressure decrements in the bottle that supplies oxygen to the astronauts in their spacesuits. The data is downlinked to Earth every two minutes. This data can then be compared, real-time to the NBL data by the flight surgeon and biomedical engineer (Klein et al. 2008). NBL metabolic rates provide useful information for flight planning and EVA monitoring. Quantifying similarities and differences between training and flight improves knowledge for safe and efficient EVAs

The end of the shuttle program did not mean the end of EVAs. Training for scheduled and contingency EVAs continues at the NBL. With far fewer scheduled EVAs, all ISS increment crewmembers now prepare using a set of standard EVA skills training profiles covering the most likely contingency and emergency repairs.

In 2005, the Anthropometry and Biomechanics Facility (ABF) at NASA JSC developed a preliminary model to assist in suit weigh-out in the NBL (Clowers et al. 2006). Suit weigh-out attempts to make a crewmember in the EMU neutrally buoyant and rotationally neutral, and helps to minimize position corrections when a subject is attempting to maintain a working posture. Correct posture without an optimal weigh-out causes fatigue and eventually causes injury (Williams and Johnson 2003a). The ABF model used underwater motion analysis, 3D body scanning, and an instrumented handrail to predict optimal weigh out conditions for a given subject size.

In addition to EVA training, the NBL has also been used to conduct EVA research. As the Advanced EVA Space Suit PLSS was entering its early design phase in 2006, an investigation was launched to determine the most appropriate location for the center of gravity of the PLSS in relation to a crewmember. The Crew and Thermal Systems Division (CTSD) at NASA JSC developed a rig that could be worn by a SCUBA diver. The rig has the total mass of the new PLSS and internal adjustable weights that can alter the location of the rig's center of gravity. The PLSS rig was also used during NEEMO (NASA Extreme Environment Mission Operations) missions 9-14, off the coast of Key Largo, FL (see next section). Valuable data was collected and

combined with the data taken during NEEMO missions to ensure suit and PLSS designs were acceptable for human performance (Jadwick et al. 2008b).

More recent testing of advanced EVA scenarios has been performed in the NBL: suited tests, in the current NASA EMU as well as the modified advanced crew escape suit (MACES), to test micro-gravity asteroid exploration and capsule-based EVA techniques. This testing has also collected human performance data and used similar timeline and task techniques to those described for Shuttle and ISS EVA training. The data collected will be used to ensure human health and performance is considered in suit, tool, task, and timeline designs.

III.2.2.2. NEEMO

Aquarius is the only operational undersea research habitat in the world. It is operated by the Florida International University (FIU). *Aquarius* was built in the mid-1980s, and was previously located in Saint Croix (U.S. Virgin Islands) before it was moved to the reef line 12 miles off Key Largo, Florida, in 1990. In these 2 locations, *Aquarius* has supported dozens of missions to study the undersea realm for several hundred marine research scientists from around the world.

Aquarius is similar in size to the U.S. Laboratory module on the International Space Station, or ISS (~15 m long \times 4.5 m in diameter). It is firmly secured to a sand patch surrounded by large spur-and-groove coral reefs on 3 sides. It sits in water 18 m (60 ft) deep, but the entrance level is actually closer to 15 m (50 ft), which corresponds to an internal pressure of ~ 2.5 atmospheres. At this depth, aquanauts living and working in the habitat become exposed to excessive levels of nitrogen within the first few hours and must commit to staying in the habitat and undergoing a decompression schedule before returning to the surface. This type of diving is called “saturation” diving, referring to the complete saturation of the body tissues by the breathing gas mixture. A diver in this condition will quickly experience decompression sickness if he or she returns to the surface without going through the requisite decompression schedule, and would most likely experience injury and possibly death if not treated. The danger is real and the environment is truly extreme, which is one of the key reasons it makes such a good analog to living in space. Aquanauts participating in these missions must utilize their training, skills, knowledge, and teamwork to ensure their safety and mission success.

The combination of isolation in a confined and extreme environment along with the ability to simulate weightlessness or reduced gravity during EVA excursions makes *Aquarius* an excellent analog for space flight, second only to the ISS itself as judged by a comprehensive assessment of all Earth-based space flight analogs (Keeton et al. 2011). NASA’s NEEMO project began in 2001 with the primary goal of astronaut training. Over time, the project evolved to include many science and engineering studies during the missions. NEEMO missions have included evaluations of the effects of communications time delay on mission operations, evaluation of telemedicine techniques, and research involving behavioral health, team cohesion, fatigue, and other physiological and psychological adaptations that occur during NEEMO missions. Other objectives have taken advantage of buoyancy while crewmembers are diving on SCUBA or umbilical-supplied diving helmets outside the *Aquarius* habitat; by attaching the appropriate amount of weight or flotation to EVA crewmembers, the effects of different gravity environments and spacesuits of different weights can be simulated. In some cases, custom-built backpacks have been used to simulate the backpacks on EVA suits except that they are reconfigurable so that the center of gravity (CG) can be moved to simulate the CG of different

spacesuit designs (Chappell et al. 2011). Crewmembers have then performed predefined tasks in the simulated partial-gravity environment to provide valuable data on, for example, the design of tasks, EVA interfaces, and hardware, and the effect of spacesuit weight and CG on EVA performance; all while taking data to ensure human health and performance of EVA.

III.2.2.3. Land-based Field Testing

Land-based field testing is a valuable and complementary aspect of EVA research that provides high-fidelity hardware along with true geologic science and actual terrain features, lending realism to the tasks and timelines that humans may need to perform while on EVA. Although land-based field testing does not provide the reduced gravity environment of gravity offload devices or underwater simulations, combined research from land-based environments provides a complete picture of all aspects of exploration destination EVAs.

NASA has used a variety of land-based field testing sites and projects for EVA systems research including Antarctic, high-arctic (Norcross et al. 2008), desert, and other field locations that simulate particular exploration destinations. NASA's Desert Research and Technology Studies (Desert RATS) tests took place from 1997-2011. Initially, these field tests were focused on evaluating advanced spacesuit and EVA systems, primarily spacesuit configurations, mobility aids, robotic assistant interaction, field test support equipment, and EVA science. The tests objectives shifted over time from characterizing the performance of EVA mobility, to evaluating EVA exploration components, and finally toward performance of integrated mission scenarios. Human interaction with rovers, habitats, robotic assistant elements, and exploration operations control centers formed the central aspects of the later field test objectives (Ross et al. 2013).

In 2012, RATS was relocated to NASA Johnson Space Center. High fidelity hardware and simulations were still used to provide a realistic research environment for EVA, although not in remote fields (Abercromby et al. 2013b).

III.2.3. Characterization of EVA Research Environments

Simulating partial gravity on Earth is difficult. While many methods exist, all have significant limitations (Chappell and Klaus 2013). The overarching goal of the IST series was to evaluate suited human performance in reduced gravity. To effectively complete this goal, partial-gravity analog environments would ideally need to allow unrestrained freedom of movement in all 6 degrees of freedom (DOF) while accurately simulating partial-gravity kinetics. After the IST series was completed, analysis was performed to understand and highlight the strengths and limitations of the current partial-gravity analog environments, and provide recommendations for improved simulators (Norcross et al. 2010a). Two different partial-gravity simulations were primarily used in the IST studies to characterize suited human performance: 1) the Johnson Space Center (JSC) Space Vehicle Mockup Facility's (SVMF's) POGO and 2) JSC Reduced Gravity Office's (RGO's) C-9 parabolic flight aircraft. Post-series analysis began with a general characterization of each environment, followed by direct comparisons from subjects doing similar tasks to evaluate human performance metrics collected in both partial-gravity environments. Next was the highlighted indirect comparisons, which looked at how human performance during partial-gravity simulation differs from expectations based on physics, models, or results from other studies. Finally, the analysis closed with considerations regarding

the usability of each partial-gravity analog environment and suggestions for improved simulations.

The ability to accurately and effectively characterize suited human performance is wholly contingent on understanding the accuracy, limitations, and usability of partial-gravity analog environments. Although parabolic flight may simulate partial-gravity kinetics better than any other environment, the high cost, volumetric constraints, limited parabola duration, and limited data-collection capabilities limit the use of the C-9 or another parabolic aircraft as a partial-gravity analog environment for studying suited human performance (Norcross et al. 2010a).

Although POGO improves on many of the major limitations of parabolic flight, it also introduces several new sources of error including increased inertia, limited DOF, and non-optimized offload kinetics. The ideal partial-gravity analog environment would combine the partial-gravity kinetics of parabolic flight with a large test area, advanced data collection capabilities, unlimited time, treadmill integration, and mock-up inclusion available with ground-based analogs such as POGO. Many of the major limitations of POGO could be improved by implementing changes in the current system or a follow-on system (Norcross et al. 2010a).

If the needed changes were to be incorporated into a new overhead suspension system, the system would provide an optimal primary test bed on which to characterize suited human performance. The Active Response Gravity Offload System (ARGOS) has been designed to simulate reduced gravity environments, and as an improved replacement for POGO. ARGOS uses an inline load cell to continuously offload a portion of a human or robotic payload's weight during all dynamic motions, which can include walking, running, and jumping under lunar or martian gravities, as well as a wide range of microgravity activities. Using a cable angle sensor, ARGOS actively tracks and follows the payload's motion in all horizontal, translational directions to maintain an accurate vertical offload force. The facility is capable of supporting surface operation studies, suit and vehicle requirements development, suit and vehicle design evaluation, robotic development, mass handling studies, and crew training with both suited and shirt-sleeved subjects (Dungan and Lewis 2013).

Currently under continuous development and improvement, ARGOS is intended to support testing, development, and training for future missions to the Moon, Mars, asteroids, or any other celestial destination. It is also intended to support both intravehicular activity (IVA) and EVA training for NASA's ongoing activities on the ISS. The current steel structure, which measures 41' x 24' x 25', accommodates movement in all 3 directions of motion (one vertical and two horizontal). This facility mitigates many of the limitations of the previously used POGO system and is enabling the start of a new generation of essential EVA research (Dungan and Lewis 2013).

However, even with all of improvements in gravity offload systems such as ARGOS, there are still limitations that cannot be removed, including restraints in the lifting path, which is restricted to the CG and anything outside of that lifting path, particularly the limbs and any accessories, will still operate within 1g kinetics. For this reason, parabolic flight and underwater buoyancy should be used for testing that requires all materials, including the subject, suit, tools, and mock-ups to be at the same partial gravity. Parabolic flight also remains a viable option for

limited verification of ground-based data, assuming the tasks are performed in the same way in both partial-gravity analog environments (Norcross et al. 2010a).

IV. CONTRIBUTING FACTORS

There are many factors that contribute to the risk of injury and compromised performance due to EVA operations. Extensive review within the EVA research community and NASA Human Systems Risk Board has delineated 24 separate contributing factors grouped within the categories of suit habitability, in-suit physical environment, EVA factors, crewmember physical state, and crewmember psychological state. The groupings as well as their potential contribution to injury and/or compromised performance are shown in Figure 1.

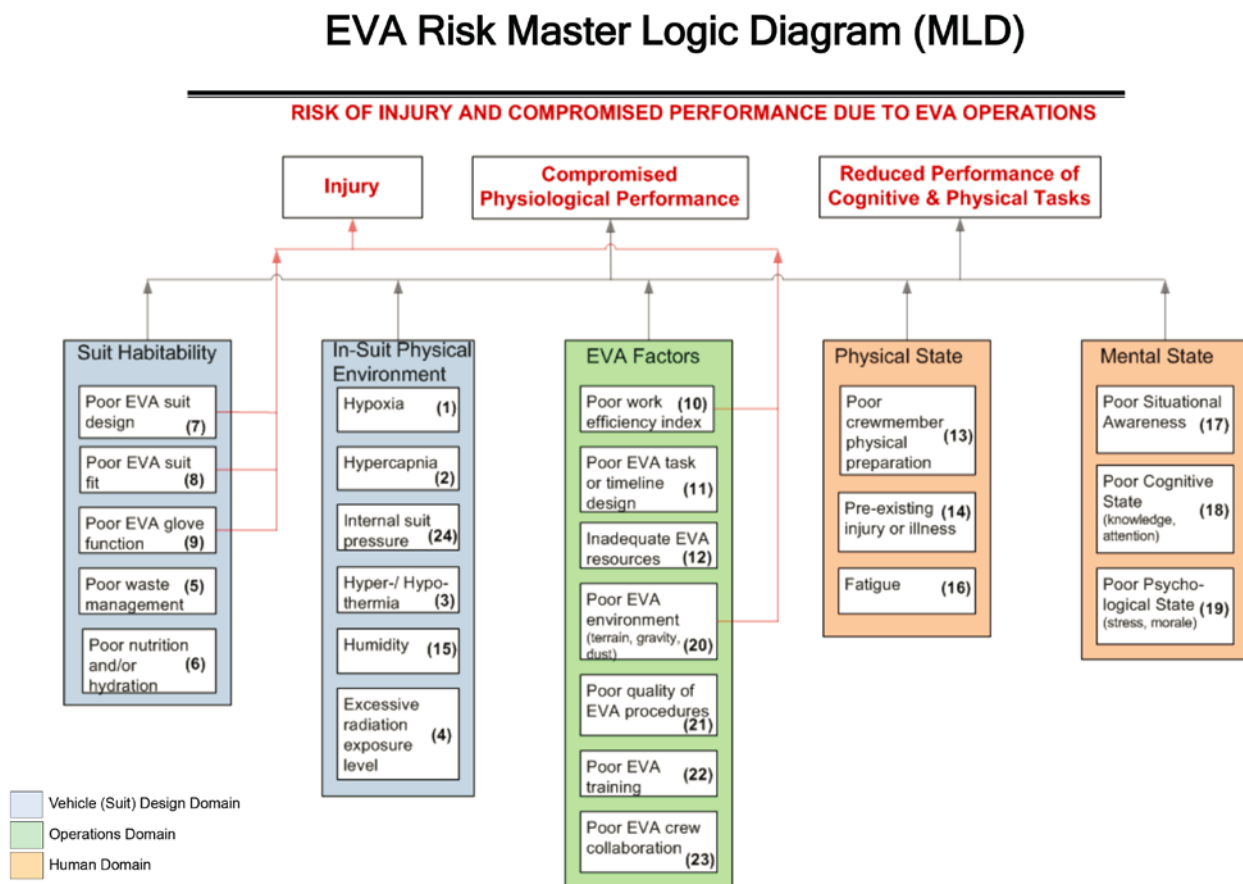


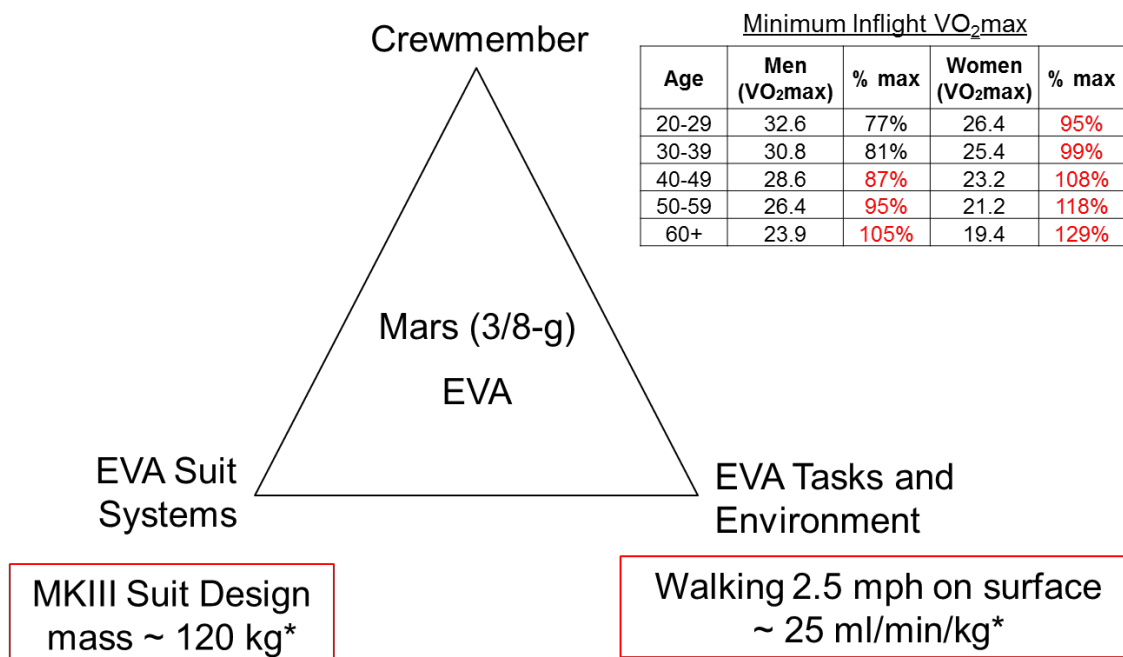
Figure 1 - EVA risk Master Logic Diagram (MLD).

While this figure is helpful, it does not describe which of the contributing factors are adequately controlled, which factors require additional research, or which research and development group is tasked with mitigating the risk. Although certain groups (Engineering Directorate, EVA Management Office, Mission Operations Directorate, Crew Health and Safety, Human Research Program, etc.) within NASA may be responsible for different factors, it is critical to keep all of these factors in mind because of the numerous possible interactions. The following sections individually address each of the categories and their contributing factors, providing an overview of the evidence for each.

IV.1. Suit Habitability

IV.1.1. EVA Suit Design

While spacesuits can have many design and technology variables, a few general factors are believed to affect human suited health and performance, namely mass, pressure, center of gravity, joint characteristics, and how well the suit can be made to fit the subject. Current suit designs for partial gravity have high mass and may be out of sync with the fitness for duty requirements for destinations such as Mars. An example of this disconnect is shown in Figure 2. This analysis contributed to a revision of the aerobic capacity fitness for duty standard and there are now several active studies aiming to reconcile this disconnect. Suit pressure, depending on suit design, has been shown to impact the crewmember's mobility and ability to complete tasks (Norcross et al. 2010d). Other factors such as poor centers of gravity have been shown to induce instability while performing some tasks (Chappell et al. 2010a; Chappell et al. 2011). Shoulder injuries and other injuries have been induced by forced motions due to spacesuit joint characteristics and fit (Strauss et al. 2005; Williams and Johnson 2003b).



* Source: EVA Walkback Test Report, NASA/TP-2009-214796

Figure 2 - EVA crewmember, suit, tasks and environment interactions. This example shows that the simple act of walking at 2.5 mph on the Mars surface in the MKIII prototype EVA suit would require near maximal or even greater than maximal VO₂ values than what was allowed in NASA-STD-3001 Volume 1 prior to Revision A in 2014 .

IV.1.1.1. EVA Flight History

Throughout the history of space flight, astronauts and cosmonauts have performed more than 400 EVAs. However, only 28 of those EVAs have been conducted in partial-gravity (i.e. lunar). Accordingly, the current understanding of suited human performance in partial-gravity environments is limited. A face-to-face summit with some of the Apollo astronauts provided valuable insight and yielded recommendations for the next-generation partial-gravity EVA suit.

Fourteen of the 22 surviving (at the time of the summit) Apollo astronauts participated in the Apollo Medical Operations Project to identify Apollo operational issues that impacted crew health and performance. In the category of EVA Suit Operations, recommendations centered on improving the functionality of the suit as well as improving human factors and safety features. The astronauts recommended increasing ambulatory and functional capability through increased suit flexibility, decreased suit mass, lower center of gravity, and reduced internal pressure (Scheuring et al. 2007).

The following excerpt from Scheuring et al. (2007) describes the astronauts' view on the need for increased suit mobility: "EVA suit mobility was more of an issue in terms of surface locomotion and energy expenditure. The crews often felt they were fighting the resistance in the suit. This was fatiguing, especially in the thighs." The astronauts pointed out that the lunar surface is more similar to an ocean than a desert. The undulating surface posed a number of challenges, including ambulating against a suit that did not allow mobility at the hip. Normal human locomotion includes flexion at the hip, knee and ankle, but the Apollo A7LB (lunar surface EVA suit) had limited ability to bend the suit at the hip and rotate within the suit. This likely contributed to the loping and hopping style gait, which relied more on knee and ankle range of motion.. The crewmember had to bend forward from the knee joint, which demanded considerably more work load on the quadriceps muscles. Therefore, recommendations on mobility centered on adding hip mobility and improving knee flexibility. One comment summarized this point well, *'Bending the knee was difficult in the suit. We need a better [more flexible] knee joint'.*"

The Apollo astronauts also strongly recommended improving glove flexibility, dexterity and fit. According to the crews, the most fatiguing part of surface EVA tasks was repetitive gripping. One crewmember stated that *"efficiency was no more than 10% of the use of the hand"* (Scheuring et al. 2007).

A comprehensive analysis was completed of all musculoskeletal injuries and minor trauma sustained in flight throughout the U.S. space program (Scheuring et al. 2009). This study identified 219 in-flight injuries, of which 50 resulted from wearing the EVA suit, making this the second leading cause of in-flight injuries. The incidence rate of EVA injuries was 0.05 per hour for 1,087.8 hours of EVA activity. This equates to an incidence rate of 1.21 injuries per day, or 0.26 injuries per EVA. The following excerpts from this study are illustrative of the types of EVA-induced injury:

"Hand injuries were most common among EVA crewmembers, often due to the increased force needed to move pressurized, stiff gloves or repetitive motion for task completion. Many astronauts described the gloves causing small blisters and pain across their metacarpophalangeal (MCP) joints. This could be due to dorsal displacement of the MCP joints against the glove in order to flex the fingers (Viegas et al. 2004). While not mission impacting injuries, they can potentially distract an astronaut from important EVA tasks. Astronauts frequently develop onycholysis (separation of nail from nail bed) after Neutral Buoyancy Laboratory training sessions, and it is possible some of these injuries represent exacerbations of underlying ground-based injuries."

However, the authors later state that pre-flight conditions were not strong predisposing factors for these injuries.

“Foot injuries also caused problems for EVA astronauts. One astronaut described an episode of ‘excruciating, searing, knife-like pain’ during an EVA. The astronaut attributed the pain to excess suit pressure bladder material inside the boot, but despite attempts at correcting the problem, the pain persisted with the development of a blister...Though the EVA was completed successfully, the astronaut described the pain from this injury as ‘on the forefront of my mind’.” “Another astronaut had similar symptoms after his second EVA with resultant numbness and pain on the dorsum of his feet.”

Pressure-associated erythema developed on the dorsal surfaces of each foot, and symptoms persisted throughout the mission and 2 to 3 weeks post-landing (Scheuring et al. 2009).

Nine of the 219 in-flight injuries were sustained by Apollo astronauts who were performing lunar surface EVAs. One Apollo astronaut suffered a wrist laceration from the suit wrist ring while working with drilling equipment, and another crewmember sustained wrist soreness due to the suit sleeve rubbing repeatedly. One crewmember injured his shoulder during a lunar EVA while attempting to complete multiple surface activities on a tight mission timeline. Unbeknownst to his flight surgeon, this crewmember later took large doses of aspirin to relieve the pain. Many Apollo astronauts noted problems with their hands. One astronaut remarked: “EVA 1 was clearly the hardest ... particularly in the hands. Our fingers were very sore.” Another Apollo astronaut remarked that his hands were “very sore after each EVA”; while another astronaut stated that following the third lunar EVA, his metacarpophalangeal and proximal interphalangeal joints (knuckles) were so swollen and abraded from a poor-fitting glove and/or lack of inner liner or comfort glove that he is certain that a further EVA would have been very difficult if not impossible. Accordingly, it is no surprise that the Apollo astronauts were adamant that the glove flexibility, dexterity, and fit be improved (Scheuring et al. 2007).

A study by Strauss describes shoulder injury; 13 of the study’s 22 participants were assessed for shoulder-related injuries, and 2 required surgical interventions (Strauss et al. 2005). There are 2 primary causes for EVA-related shoulder injury: restriction of normal shoulder movement by the Hard Upper Torso (HUT) and supporting body weight against the HUT. Depending on the lateral position of the scye bearings, scapulothoracic motion can be restricted, preventing normal shoulder abduction and adduction. To compensate, astronauts rely more heavily on the rotator cuff muscles that normally stabilize the joint, causing overuse of the rotator cuff and leading to injury (Williams and Johnson 2003b). Additionally, as astronauts shift within the suit during training, their bodies press up against the HUT, resting their weight on their shoulders. This is particularly true when the astronaut is in an inverted position, either fully head down, face forward, or face upward. Resting weight on the shoulder impinges on the rotator cuff muscles, causing tears and pinched nerves, in addition to causing uncomfortable pressure contacts (Strauss 2004; Williams and Johnson 2003b). Inverted NBL training is still performed, but in limited duration.

Injury data has been compiled from the Lifetime Surveillance of Astronaut Health (LSAH), and an initial characterization of the data has been completed. Rigorous criteria for categorizing astronauts as injured or uninjured are being created with input from NASA subject matter experts. Data analysis is ongoing to compare astronaut anthropometry and suit components to injury.

Limb joint injuries occur when the convolute suit joint is not aligned well with the body joint, so the propensity for injury is increased (Benson and Rajulu 2009; Strauss 2004). Hip and trunk injuries on orbit are rare, and are primarily caused by impact and rubbing with the HUT, waist bearings, and soft elements resulting in abrasions and contusions. In training, additional injuries are seen in both the supine and prone positions because the weight of the astronaut is supported by the HUT and the ventilation tubes of the LCVG. This pressure can lead to skin indentation and reddening (Scheuring et al. 2009; Strauss et al. 2005).

Many EVA tasks are performed using footholds as the primary restraint. Although the EMU is designed with limited lower body mobility, astronauts must produce a counter torque by flexing leg and ankle muscles to maintain proper orientation while they work. Poor fitting boots and boot inserts allow the astronaut to rotate backward, causing the foot and toes to impact and rub against the boot (Strauss 2004). Additional discomfort is caused by bootie and pressure layer wrinkles, which cause blisters, contusions, abrasions and loss of feeling. In one instance, this almost led to early termination of the EVA (Scheuring et al. 2009). In training and during experiments to evaluate planetary locomotion and exploration procedures, the shifting body also causes the top of the foot and distal toes to impact the boot (Norcross et al. 2009; Strauss 2004).

Data has been collected in the Mk-III spacesuit technology demonstrator, mostly in simulated lunar gravity and using the POGO weight offload system (Norcross et al. 2010b; Norcross et al. 2010d; Norcross et al. 2009). No similar data using similar study design has been collected using suit prototypes other than the Mk-III, therefore it is not currently known if the effects of suit design parameters are limited to the features of the Mk-III prototype. Additionally, the limitations of the POGO system used during previous testing are believed to have had negative effects on the results. The ARGOS system substantially improves the accuracy of the data collected (Norcross et al. 2010a).

Physiologists and physicians have used various analog environments to study the effects of suit weight, mass, CG, pressure, biomechanics, and mobility on human performance. Test activities have been designed to characterize performance during ambulation and exploration-type tasks such as; ambulation on both level and inclined surfaces; ambulation while carrying a load, rock collecting, shoveling, and kneeling. Other studies examine recovery from a fall, and simple exploration and construction tasks using hand tools and power tools. Data collected includes metabolic rates, time series motion capture, ground reaction forces, subjective ratings of perceived exertion (RPEs) (Borg 1982), and operator compensation using a relative subjective scale.

During a study conducted to characterize upper body movement and contact forces inside the spacesuit during mission-realistic movements, a subject noted increased load on his shoulders while returning to standing position after tightening a boot. During a prone-to-recovery task, the

subjected noted the suit shifted over his body creating discomfort in his hands, back, and shoulders (Anderson et al. 2015). To perform a functional mobility test in the EVA suit, the subjects had to crawl on knuckles or elbows. The most difficult task was moving from prone to standing, and most subjects were not able to complete this due to poor suit-fit that caused their hands to slip out of the gloves (England et al. 2010).

Results from tests conducted on the POGO system have begun to characterize the metabolic cost, biomechanics, and subjective factors that are associated with ambulation and task performance in a suit in partial gravity. These tests have characterized the baseline metabolic cost of suited ambulation in lunar gravity across a wide variety of speeds, and have considered factors such as suit weight, inertial mass, suit pressure, and suit kinematic constraints and stability. Figure 3 shows a model describing the current understanding of how these factors contribute to the increased metabolic cost of suited ambulation in the MK-III suit (Norcross et al. 2010d). The parameter that had the largest impact on metabolic rate was suit weight, which is a function of the suit's mass and the gravity field it is being operated in. Pressurizing the spacesuit increased metabolic effort, but variations in suit pressure make little difference. Factors such as inertial mass and stability in reduced gravity were lumped into a residual category that was not systematically evaluated. Future studies that can properly increase the mass of the EVA suit and compare different mass options in different gravity fields may provide clarification to determine if it is the mass or weight of the suit that most affects human performance.

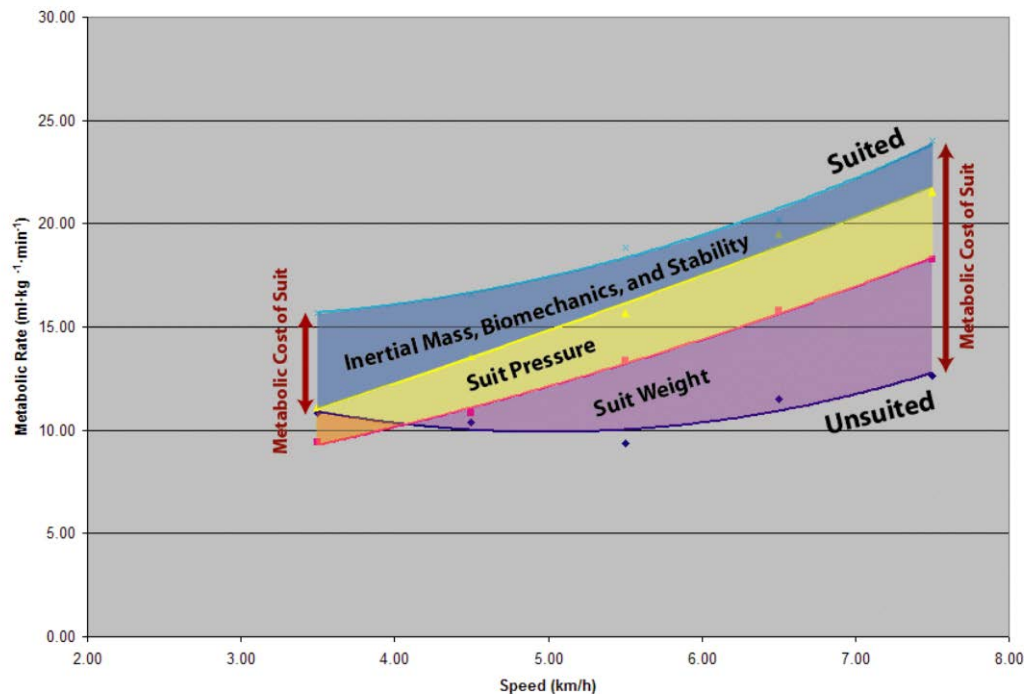


Figure 3 - Proposed model for suit design parameters that contribute to the metabolic cost of ambulation in lunar gravity wearing the Mk-III suit.

Based on the POGO test results, a predictive equation for metabolic rate has been proposed that includes factors such as subject anthropometrics, locomotion speed, suit pressure, and suit weight (Figure 4). As more data are collected, this algorithm will be expanded into an EVA consumables calculator where inputs on the subject, suit, and type and duration of tasks can be entered to predict a metabolic profile and the expected consumables usage. This algorithm is an example of a design tool that can help in the development of spacesuits that increase efficiency in crew health and performance based on different operational concepts.

This is just one example of how operational concepts will play a large role in determining requirements. If a crewmember is only expected to walk slowly, the suit weight may not be a critical design parameter; but if a long, e.g., 10-km/6.2-mile, walk-back is a contingency, the suit weight will be absolutely critical to mission success as well as crew performance and risk of injury.

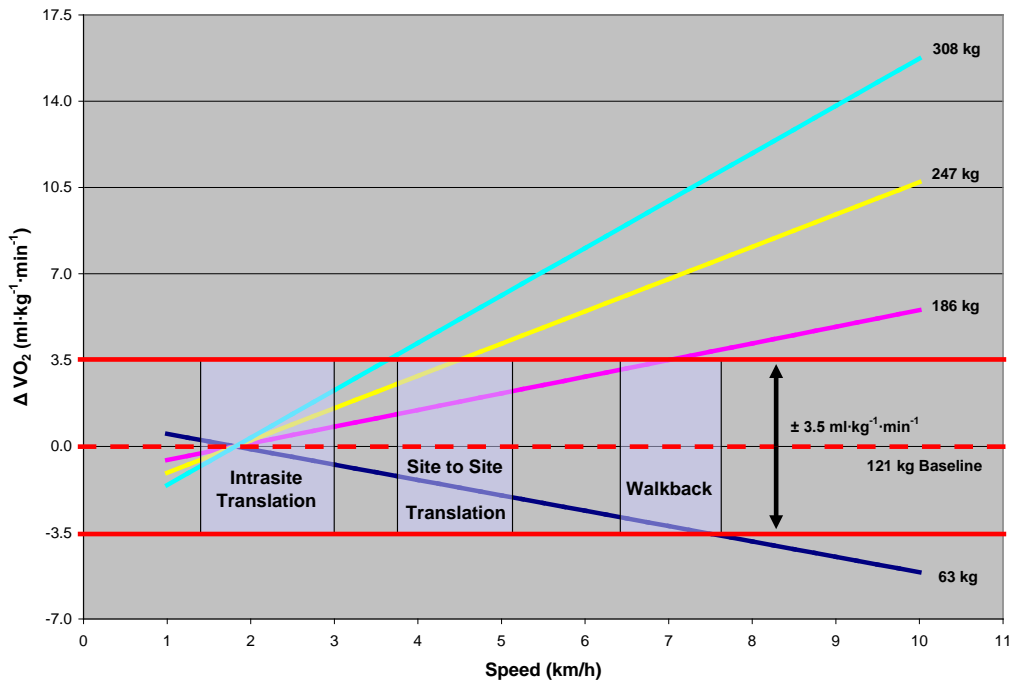


Figure 4 - Model of the effect of suit weight on metabolic rate across speed of ambulation based on the Mk-III data from the POGO.

In addition to ambulation, the effect of various suit weights and pressures has been examined during a variety of exploration-type tasks, such as shoveling and picking up rocks. Figure 5 describes the metabolic cost and Gravity Compensation and Performance Scale (GCPS) ratings for 6 subjects during the rock transfer task as a function of gravity or total system weight. Both the objective and the subjective ratings show the same trends, which surprisingly indicate that an increased system weight is associated with better performance. Other tasks (shoveling and a construction task busy board) demonstrated the same trend. However, this testing was performed at a single suit mass (due to limitations of the POGO system) with varied weight

offload to simulate different suit weights. Since testing was not performed with mass variation, there is still much to be learned by varying suit mass in a given simulated gravity field. The GCPS quantifies the suit operator compensation that is required for optimal task performance, which is defined as being equivalent to 1-G shirt-sleeved (i.e., unsuited) performance. Ratings of 1 to 3 indicate acceptable performance, 4 to 6 indicate that modifications are recommended for optimal performance, and 7 to 9 indicate that modifications are required; a rating of 10 indicates that the task cannot be performed under the current conditions.

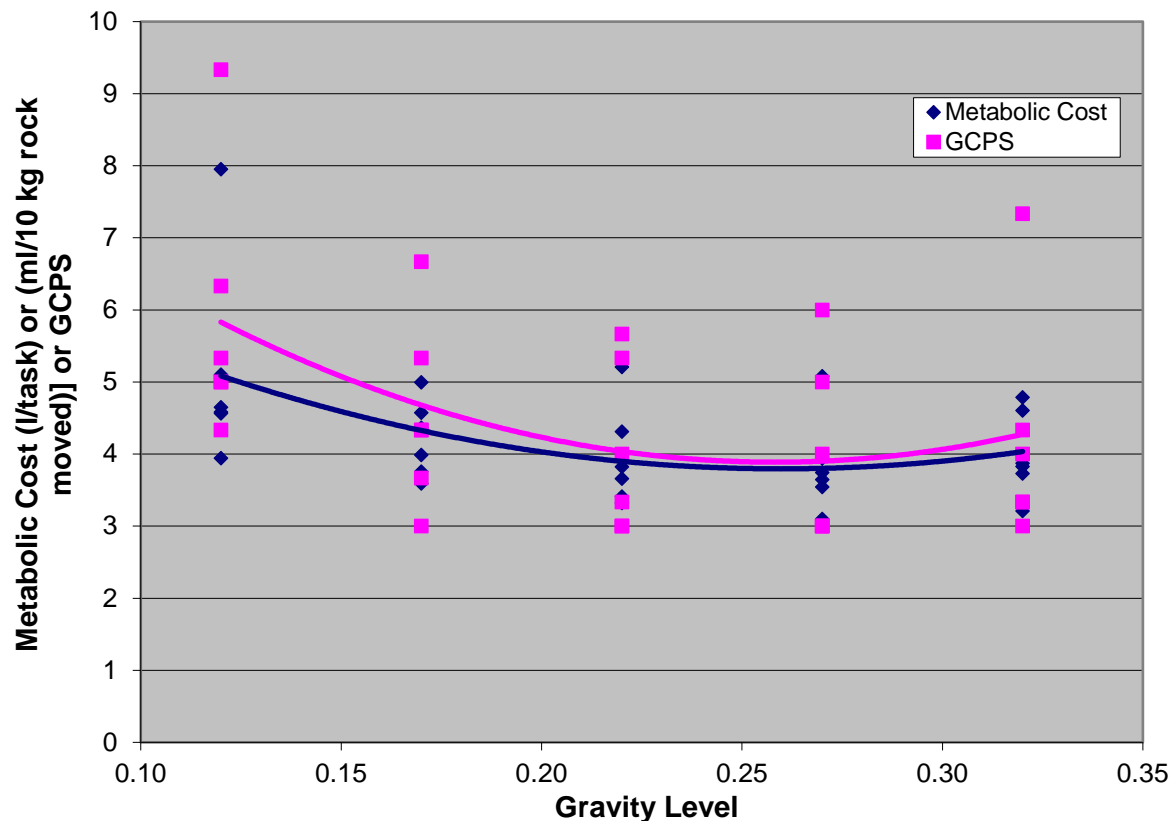


Figure 5 - Effect of suit weight on metabolic rate and subjective GCPS ratings during exploration tasks.

Biomechanical impacts of the suit are more difficult to differentiate; however, they may be critical to understanding skeletal muscle and bone loss in fractional gravity and for developing countermeasures against such losses. A key biomechanical finding relates to ground reaction force (GRF), which was higher during ambulation in suited conditions than in unsuited conditions and also increased as gravity increased. However, the GRFs were still lower than those that a crew member would normally experience on Earth. This suggests that EVA performance on a reduced-gravity planetary surface may not provide sufficient loading to protect against bone loss, thus indicating the continued need for exercise countermeasures (Norcross et al. 2010d; Norcross et al. 2009).

Recognizing that not all ambulation on a planetary surface will be similar to that on a level treadmill, initial studies were completed to characterize the effects of incline and terrain on metabolic rate. Tests on inclined walking trials inferred that the metabolic cost due to factors

other than suit weight were almost zero, suggesting spacesuit factors that are not well understood (Norcross et al. 2010d), or, more likely, a problem associated with accurately simulating inclined ambulation using the POGO.

In addition to the above stated parameters, the Apollo Program demonstrated that suited CG may be an important variable that affects human performance. Studies have evaluated CG in the underwater environments at NEEMO and the NBL. Crew performance was assessed during representative planetary exploration tasks using a single EVA suit weight and mass with different CG locations. A reconfigurable backpack that has repositionable weight modules was used to simulate CG locations (perfect, low, forward, high, aft, and NASA baseline) under the assumption of a 60-lb. suit, a 135-lb. Portable Life Support System (PLSS), and a reference 6-ft, 180-lb subject. Subjects used the GCPS rating tool to evaluate the CG locations. As shown in Figure 6, subjects preferred (with lower GCPS score) the perfect, low, and forward CGs over the high, aft, or NASA baseline (CTSD) CGs (both high and aft, similar to the Apollo suit CG). These findings suggest that a conventional backpack PLSS may not be optimal and that alternative configurations should be considered (Jadwick et al. 2008a).

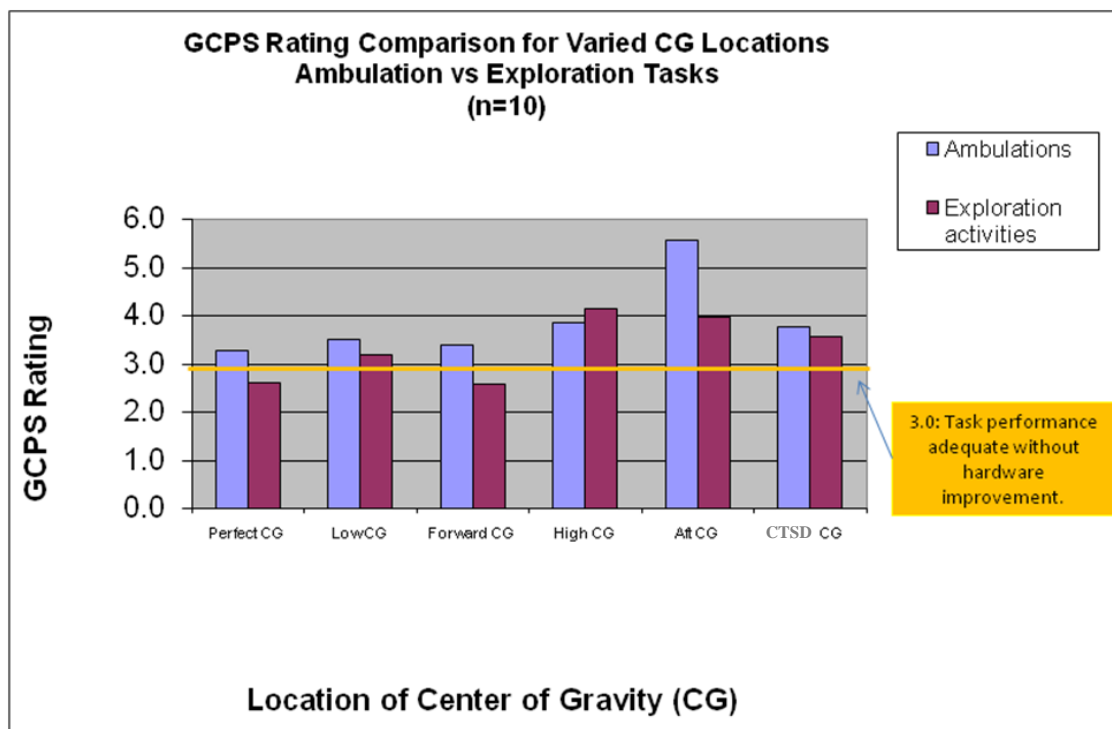


Figure 6 - GCPS ratings for suit center of gravity (Jadwick et al. 2008a).

IV.1.1.2. Injury to Specific Body Locations

To adequately prepare for mission EVAs, astronauts undergo extensive ground-based training at the NBL, which provides controlled neutral buoyancy operations to simulate the zero-g or weightless condition. Objects are configured to be neutrally buoyant by using a combination of weights and flotation devices so these objects seem to “hover” under water, thus enabling large, neutrally buoyant items to be easily manipulated, much as they would be in orbit. The significant

increase in EVA NBL training to support the construction and maintenance of the ISS led to an apparent increase in the incidence of symptoms and injuries experienced by crewmembers operating in the EVA suit.

A study that was conducted from July 2002 to January 2004 identified the frequency and incidence rates of symptoms by general body location and characterized the mechanisms of injury and effective countermeasures (Strauss 2004). During this study, 86 astronaut-subjects were evaluated in the NBL during 770 suited test sessions. Symptoms were reported by the test subjects in 352, or 45.7%, of the sessions. Of these symptoms, 47% involved hands; 21% involved shoulders; 11% involved feet; 6% each involved arms, legs, and neck; and 3% involved the trunk.

A. Hand Injury

Hand injury symptoms of primary concern were fingernail delamination, which was thought to result from excess moisture in the EVA gloves and axial loading of the fingertips (Figure 7). There were also abrasions, contusions, and 2 cases of peripheral nerve impingements related to glove fit and hard point contact compressions. Several studies have followed up on hand related injury and are discussed in section IV.1.3 EVA Glove Function, because the glove is considered a separate system within the EVA pressure garment.

B. Shoulder Injury

Shoulder injuries were proposed to be due to hard contact with suit components and strain mechanisms (Figure 7). A shoulder injury tiger team was created in December 2002 at the NASA Johnson Space Center to evaluate the possible relationship between shoulder injuries and EVA training at the NBL (Williams and Johnson 2003b). This team surveyed 22 astronauts who had participated in EVA training. In this group, 14 astronauts (64%) had experienced some degree of shoulder pain that they attributed to EVA training. A majority of these cases were classified as minor, resolving within 48 to 72 hours. However, 2 of the 14 subjects required surgical repair after injury. It was determined that the major risk factors leading to injury were: the limited range of motion in the shoulder joint due to use of the “Planar” HUT of the EVA suit, tasks in inverted body positions during NBL training, overhead tasks, repetitive motions, use of heavy tools, and frequent training sessions. Additional minor risk factors included suboptimal suit fit and lack of appropriate padding or load alleviation (Williams and Johnson 2003b). While the astronaut-tool-EMU simulation package may be neutrally buoyant as a whole, the astronaut is not weightless within the suit. In the inverted (head-down) position, gravity causes the astronaut to “fall into” the head of the spacesuit, pressing the shoulders into the HUT of the suit. This further limits scapulothoracic motion of the shoulder (Viegas et al. 2004). Key elements that can mitigate in the risk of shoulder injuries that are associated with EVA training include redesign of the EMU shoulder joint or development of the next-generation suit for ISS EVA, reduction of high-risk NBL activities, optimization of suit fit, and continued emphasis on physical conditioning (Williams and Johnson 2003b).



Figure 7 – Example fingernail and shoulder trauma sustained during EVA training.

C. Feet Injury

Injury occurs mainly on the top of the feet and on distal toes, and is associated with issues of boot fit. The foot is not well protected in the EVA suit, and there is no arch support built into the boot sizing inserts. The boot does not protect the feet from hard contact from the 1g effect on the front of the toes that takes place in training. There is also hard contact on the top of the feet while in the portable foot restrains. (Straus 2004)

D. Arms, Legs, Neck, and Trunk Injury

Elbows and knees were the most common area of pain or injury in the arms and the legs. While most of the symptoms and injuries sustained during EVA training were “mild, self-limited, and controlled by available countermeasures,” some “represented the potential for significant injury with short- and long-term consequences regarding astronaut health and interference with mission objectives” (Strauss 2004). Neck pain was mostly due to the shoulder inserts not placed properly. Problems with the trunk were due to hard contact with components within the suit.

During the 10-km EWT, subject discomfort levels were recorded and a medical monitor examined the subjects for signs of suit-induced trauma at the completion of the test. In terms of discomfort, the mean rating was 1.5 ± 1.1 (SD), which is “very low” to “low” on the 10-point discomfort scale. The knee area and the feet/toes were the most frequent sites of discomfort during and after the test (Figure 8). Fatigue and/or muscular tightness were reported most commonly in the quadriceps, thighs, gluteal muscles, and lower back (Norcross et al. 2009).



Figure 8 - Knee and foot trauma sustained during 10-km EWT (Norcross et al. 2009).

IV.1.1.3. Incidence of Pain during Extravehicular Activity (EVA) in Space flight and the Use of Pharmaceutical Countermeasures

Fewer than 20 lunar surface EVAs were performed during the entire Apollo Program. Scenarios evaluated during NASA Constellation Program's Architecture Team for lunar exploration included as many as 30,000 hours of lunar exploration EVA time. Anticipating that there could be pain and injury experienced during these EVA excursions, NASA has proposed countermeasures including on-site medication treatment. During long-duration space missions, pain management may be required for unanticipated accidents (e.g., fractures of bones, lacerations, or blunt trauma), medical conditions such as appendicitis, or a perforated viscus (IOM 2001). Accidental wounds (such as lacerations and open fractures) may become contaminated and require therapeutic administration of antibiotics to prevent devastating infectious complications (Singer et al., 1997; Luchette et al., 2000).

An analysis of postflight medical debrief data, and the results of a data mining effort to assess minor clinical conditions occurring during Space Shuttle flights STS-1 through STS-94 revealed that approximately 37% of all medications used by astronauts on those flights was for pain (Putcha et al, 2012). NASA's LSAH program proactively collects data on astronaut medical care and workplace exposures, especially those occurring in the training and space flight environments, and conducts operational and health care analyses to look for trends in exposure and health outcomes. NASA's Life Sciences Data Archive also includes human subject data derived during space flight, as well as data from analog studies. Ninety percent of the medical conditions that have affected NASA astronauts during space missions can be treated or mitigated by pharmaceutical countermeasures based on the Integrated Medical Model 2012 update (personal communication with Vernie R. Coleman Daniels, M.S., R.Ph. Research Pharmacist, KBR Wyle).

IV.1.1.4. Strength and Mobility Limitations

The EVA suit compromises crewmembers' mobility and decreases their strength. During a strength assessment, test subjects demonstrated reduced overall strength when wearing the EMU as compared to unsuited values (Amick et al. 2015). Two different support systems were tested: free standing and constrained standing. No overall difference in strength was observed during these support conditions, verifying that the decrease in strength was due to the suit itself.

Recently completed studies and currently ongoing studies have evaluated the range of motion differences between suited and unsuited conditions. Although results are not yet published, it is well understood that a person's range of motion is also compromised in the EVA suit. A decrease in the crew's overall reach is an issue when planning and designing tasks. Since the crewmember will have a limited space that they are able to reach in a suit, all tasks will have to be designed to be within those parameters.

IV.1.1.5. Contact Pressures within the Suit

As described in Section 1, contact with the inside of the suit is a potential risk factor for injuries to the crewmember. Contact pressures injuries may be more frequent when the subject is operating inverted in 1-g during training in the NBL. Recent studies in the ABF have attempted to characterize these interface pressures, particularly at the shoulder.

Measuring interface pressure at the shoulder is complex due to the effect of temperature on interface pressure measurement systems, the distortions associated with bending of the pressure sensitive device, and shifting of the pressure mat on the skin, all of which introduce uncertainties in where pressure is actually applied on the body. These complexities are magnified when the pressure mats are placed inside a suit, because delicate connectors tend to get mangled as a subject is ingressing the suit or moving around within the HUT.

Despite the challenges of collecting data on interface pressure, studies are ongoing with Novel pressure mats placed within a custom garment at the shoulders of the EMU. In the past, only location of maximum force was examined, whereas recent advances in data processing have improved the accuracy of the force magnitude measurements. This new analysis method can be used to retroactively examine data from past tests, and assess how pressure magnitudes vary during specific movements or tasks. In particular, work is focusing on linking the pressure mat data with motion capture data, which will determine if there is a specific region in the reach envelope that induces the greatest contact pressures on the shoulder.

IV.1.1.6. Alternative Suit Design Technologies

An alternative suit pressurization technology called Mechanical Counter Pressure (MCP) may provide a light and highly flexible alternative to traditional gas pressurized spacesuits by compressing the body with tight form-fitting garments. MCP suits are based on the principle that physically compressing regions of the body would pressurize the body enough to allow the wearer to operate in hypobaric environments. Applying elastic tension over every surface of the body alleviates the need to maintain a perfectly airtight membrane (Anderson 2011) (which can be damaged, rendering the entire suit inoperable until it's patched), thus dramatically increasing safety and reliability, however it creates several additional engineering problems that are prevented in the current gas-pressurized suit.

It has been proposed that MCP suits have elastic garments that cover the entire body (excluding the head, which is placed inside a traditional helmet); however, this elasticity introduces difficulty in donning the suit and maintaining uniform pressure across the body. Areas such as the back of the hand, knees, or spinal trough may require supplemental devices in order to transfer the pressure to the skin (Waldie et al. 2002a; Waldie et al. 2002b). Small folds in the fabric could also lead to fluid pooling in the region, and proper tailoring to contour the body regardless of posture or position has proven difficult. Additionally an MCP suit would also provide no air convection to either warm or cool the body, thus relying on the body's natural temperature control mechanisms. Operationally speaking each suit must be custom made for an individual crewmember and maintain a “second skin” like fit throughout the entirety of the mission.

IV.1.2. EVA Suit Fit

The extent of performance comprises and injury risk due to suit design alone is complex to assess because one must also factor in suit fit. An EVA suit tailored for a 95th percentile male is almost guaranteed to be a problem for a 5th percentile female. Therefore, EVA suit fit must be characterized and controlled to understand how suit design affects physiological performance and injury risk.

Suit sizes and subject anthropometric accommodation capability will most likely be rather limited in any suit development program. For the Constellation Program planning crew anthropometry ranged from 1st percentile females to 99th percentile males (NASA 2010). Additional complexity stems from the fact that no one person is 99th percentile or 1st percentile in all dimensions – rather, human shape has immense variety, which can only be characterized using multivariate methods that account for different combinations in dimensions. A human can easily have a long torso and disproportionately short legs, or a head size that is not easily accommodated by a standard helmet. Custom tailoring a spacesuit to each individual astronaut's physical properties may be cost prohibitive, but if suit fit is not appropriate, NASA runs the risk of losing that crewmember's ability to perform EVA with acceptable performance and low risk of injury.

It is possible that EVA tasks on exploration environments cannot be performed by all crewmembers in the currently planned suit design, which would limit EVA responsibilities to only certain crewmembers so that crew health and performance will not be compromised. If that were not possible, some mission objectives could be lost or reduced. Other potential effects of inadequate suit fit may be: inability of the crewmember to complete EVA tasks within the time allotted; mission and EVA timeline deviations; exploration tasks cannot be completed; EVA crew physical and mental workload above acceptable levels; acute or chronic injury resulting from inadequate suit fit.

Relatively little is known about how a subject moves inside of a space suit in order to make the suit perform necessary movements. However, it is known that inadequate suit fit can contribute to injury and the ability to adequately perform necessary tasks. It is hypothesized that some injuries are caused by poor suit fit, shifting within the suit, improper use of protective garments within the suit, and repetitive motion working against an inadequately fitted suit

(Benson and Rajulu 2009; Strauss 2004; Williams and Johnson 2003b). While suit fit seems to be a critical element in preventing astronaut injury, there is no universal solution that provides for appropriate spacesuit fit and comfort. Achieving the best fit is highly individualized and one crewmember may experience uncomfortable “hot spots” in an area that another individual does not. It has been shown that even between EVA training sessions minor adjustments sometimes need to be made to a suit to achieve the best fit (Moore and Gast 2010). Additionally, a person’s body dimensions, especially height, change as they move into microgravity (NASA 2011b). Finally, movement and mobility while working in the suit may be unnatural due to each spacesuit’s natural kinematic programming (Cowley et al. 2012). Astronauts eventually learn to change their biomechanical movement strategies, rather than attempting to move as they do unsuited (Moore and Gast 2010). There is currently no adequate characterization of how a person moves relative to a spacesuit while performing tasks and how this relates to suit fit. Initial attempts to quantify body joint kinematics within a suit and the resulting suit movement found a 25 degree larger knee angle for the subject’s body then the movement of the suit when using the Contingency Hypobaric Astronaut Protective Suit (CHAPS) (Kobrick et al. 2012) for lower body motions.

There are no formal methods for objectively defining suit fit. Anthropometric measurements of the crewmember are determined and an initial suit fit is determined by a proprietary algorithm (NASA). After an initial suit fit check, the fit can be adjusted based on subjective feedback between the crew and suit engineer. Experience in both the microgravity training and flight environments provides the crewmembers and suit engineers with some knowledge about how suit fit may differ in training and flight. Suit fit is considered such an important factor that an on orbit fit check now occurs about a week before a planned EVA. This allows the crewmember to adjust his or her EVA suit if needed based on any changes in-flight.

Although much effort is placed on this iterative process of suit fit, the reality is that the final suit fit can only be classified as the best achievable suit fit for that individual subject. Two people with their best achievable fit in the same spacesuit may have important differences in absolute suit fit that could contribute to injury risk or compromised performance. With no method to validate suit fit, this creates a significant knowledge gap that is actively being addressed by several different efforts.

In 2015, the ABF assessed the feasibility of using indexing pads to mitigate some fit issues within the EVA suit. The idea was to use custom padding configurations to fill in some of the dead space in the suit, with the intention of improving stability, maneuverability, and ability to perform tasks. A similar system of pads is used to fit subjects within the shuttle EMU, particularly when there is a large gap between the subject and the suit. Results of the study indicated that a back pad may assist subjects in controlling the upper body of the suit, and reduce the propensity of the hands to come out of the gloves (a common issue for tasks such as crawling). The back pad also reduced torso over-rotation while suited, particularly for smaller subjects, again suggesting better indexing at the upper body. However, even when fully padded, the smallest subject was unable to perform some functional tasks. Part of their restriction may have been caused by the length of the torso in the tested suit, since they indicated that the hip bearings, meant to align with their hips, were more aligned with their thighs.

Determining objective suit fit using internal suit sensors remains a major topic of interest, but it is difficult to execute. Often, these studies are limited to proving the feasibility of the sensors or evaluating only one aspect of suit fit such as using pressure mat data at the shoulder while syncing motion capture to show which motions or body postures induce the highest pressure. Of some concern with this effort is a poor understanding of the pressure threshold that results in injury. Also, the addition of sensors and the resulting wires and data collection needs during testing often compromises suit fit and mobility, and changes the way the subject moves. However, these issues will start to resolve as new smaller sensors become available and wireless capabilities increase.

Assessing suit fit is a primary aim of the EVA Human Health and Performance Benchmarking study. Subjects will be given their nominal suit fit at the time of testing based on sizing information from their fit check and subsequent suited exposures. The quality of that fit will be evaluated with subjective queries relating to aspects such as discomfort, indexing (spacing within the suit volume), alignment between the body and suit joints, and mobility. Both the suited subject and the suit test engineer will be asked questions pertaining to suit fit. Questionnaires were developed based on existing methods used by the suit engineer to fit subjects, with additional questions developed by the study team to assess other aspects of suit fit that may affect performance. Certain portions of the questionnaires will be asked at donning and doffing of the suit, and between tasks whenever possible, to capture subjects' assessments of specific tasks. Results of the suit fit assessment will be analyzed in comparison to suited human performance data to evaluate indications of suit fit affecting performance.

Some additional difficulties with defining suit fit include consideration of the environment. It is difficult to assess suit fit in a partial-gravity test on Earth because the crewmember remains in the 1-g environment. During partial gravity overhead suspension, the suit is lifted and the crewmember falls into the suit. During 1-g operations, the full weight of the suit is supported by the crewmember via shoulder straps and a waist harness. Neither of these conditions are consistent with exactly how a crewmember and EVA suit will interact in actual partial gravity conditions and both conditions may require slightly different suit fits due to the different interactions.

Another issue associated with suit fit has arisen while testing the MACES as an EVA suit. To achieve a fit that optimizes for EVA, the crewmember is placed in a suit notably smaller than would be his/her normal IVA fit. Based on subjective feedback, an IVA sized suit would likely not be acceptable for EVA, and an EVA sized suit would also not be acceptable for IVA operations. Further development will be needed, but this begins to describe some of the difficulties associated with suit sizing.

The finalized version of any formal suit fit assessment must eventually be analyzed for reliability and validated in repeated-measures suit-fit sizing and performance studies to quantify the effect of suit fit on performance.

IV.1.3. EVA Glove Function

There are documented cases from the Space Shuttle program, ISS, and NBL training of hand injuries and hand fatigue while using current gloves, EVA systems, and tools (Viegas et al. 2004)

(Strauss et al. 2005). Minor to moderate glove-induced trauma from EVA and during EVA training in the NBL are the most frequently reported injuries. These injuries are specific to the microgravity EVA environment, where the crewmember performs the majority of tasks with his or her hands. Injury rates are likely not going to be the same in the planetary environment, where the crewmember will travel by foot and will not have to work to maintain a posture because gravity will secure the body and provide more Earth-like kinematics.

It is very expensive to custom tailor spacesuit gloves for individual astronauts, but if an astronaut cannot execute a task properly in a non-custom spacesuit glove, the ability to perform EVA effectively may be comprised. Many factors may be contributors to hand injury beyond glove design (length of EVA, suit pressure, tool/task design) and taking a system view may provide for an overall more effective and efficient way to lower the risk of poor crew health and performance due to hand issues.

Opperman et al. (Opperman et al. 2010b) evaluated data from 232 crewmembers' injury records and anthropometry, and found no significant effect of finger-to-hand size on the probability of injury. However, circumference and width of the metacarpophalangeal (MCP) joint were found to be significantly associated with injuries. A multivariate logistic regression showed that hand circumference had the dominant effect on the likelihood of onycholysis. Male crewmembers with a hand circumference > 22.86 cm (9 inches) have a 19.6% probability of finger injury, and those with hand circumferences < or = 22.86 cm (9 inches) only have a 5.6% chance of injury. Findings were similar for female crewmembers. This increased probability might be due to constriction at large MCP joints by the current NASA Phase VI glove. Constriction could lead to occlusion of vascular flow to the fingers and increase the chances of onycholysis. Injury rates are lower when using gloves such as the superseded series 4000 and the Russian Orlan, both which provide more volume for the MCP joint.

Jones (Jones et al. 2008) used the current EMU configured with a ventilation tube that extended down a single arm of the suit (E) and compared with the unventilated arm (C). Skin surface moisture was measured on both hands immediately after glove removal, and a questionnaire was administered to determine subjective measures. Astronauts (n=6) were examined before and after NBL training sessions. Consistent trends were discovered in the reduction of relative hydration ratios at dorsum (C=3.34, E=2.11) and first ring finger joint (C=2.46, E=1.96) when the ventilation tube was employed. Ventilation appeared more effective on the left versus the right hand, implying an interaction with hand anthropometry and glove fit. Symptom score was lower on the hand that had the long ventilation tube relative to the control hand in 2 out of 6 EVA crewmembers.

To determine design requirements that could reduce injury, an investigator team reviewed all existing hand related injuries in the LSAH database and the accompanying risk factor variables such as demographic characteristics, hand anthropometry, glove fit characteristics, and EVA training/flight characteristics (Charvat et al. 2015). Risk factors for hand injury were: smaller hand anthropometry, longer duration suited exposures, and improper glove-hand fit as calculated by the difference in the anthropometry middle finger length compared to the baseline EVA glove middle finger length. Within this report, analysis of fingernail delamination resulted in contradictory findings to those reported previously (Opperman et al. 2010a). This disparate result is less likely a true contradiction than a result of inconsistent reporting and recording of EVA

injury data. The most important result of this glove injury data mining was the recognition of a need to consistently record all suited exposures and suit related trauma. The Suit Exposure Questionnaire and database was implemented at NASA JSC in late 2016 with the goal of including this as part of every human suited event at JSC in 2017. This tool will determine likelihood of injury due to suited exposure and provide a way to parse the consequence of these injuries as well.

IV.1.4. Waste Management

Waste (i.e. urine, feces) management is an important factor in EVA suit design. The duration of the EVA governs waste management needs. The longer the EVA, the more likely it is that crewmembers will need to urinate or defecate during the EVA. This need is currently managed through the use of maximum absorbency garments (MAGs) worn by crewmembers to contain waste products during an EVA as necessary. In addition, crewmembers have been known to adopt a low residue diet and lower intake of water prior to EVAs, so as not to have to utilize the MAG. While these methods may be effective at reducing the chance of needing to urinate/defecate during an EVA, they may not be commensurate with long term health and performance as they might negatively impact crewmember hydration and nutrition.

Potential methods for mitigating this contributing factor include shorter duration EVAs that preclude the need for substantial waste management. However, implementing shorter duration and more frequent EVAs could decrease that overall work efficiency if the overhead associated with O₂ prebreathe and suit ingress/egress is not decreased. Alternately, the number of EVA hours could be reduced by employing pressurized roving vehicles and/or robotic assistants to complete some of the work that has been classically done only by EVA.

If waste is not managed appropriately during EVA a planned long-duration EVA may have to be shortened and mission objectives could be lost. Also, acute or chronic injury or illness may occur due to regular use of existing waste management methods over an extended duration mission and frequent EVAs.

The development of an improved in-suit urine collection device was recommended by the Apollo astronauts. In some cases during lunar surface EVAs, astronaut urine was not fully contained and resulted in skin irritation (Scheuring et al. 2007). Improved in-suit waste management systems will become critical in the contingency return to Earth, a scenario where the crew is required to be suited for as many as 144 hours lest the vehicle be unable to maintain pressure. Exposure to urine and fecal waste products for that length of time may lead to skin breakdown, cellulitis, and sepsis.

IV.1.5. Nutrition and Hydration

Proper hydration and nutrition are just as important, if not more important, during EVA as they are during the remainder of a space mission. The duration and metabolic demands of an EVA directly inform required nutrition and hydration needs. The longer duration and/or more physically demanding an EVA is, the more nutrition and hydration are required. Hydration needs in the EMU are currently managed through the availability of an in-suit drink bag (IDB) that is mounted to the inside of the hard-upper torso (HUT) of the suit. The IDB can hold 1.9 liters (32

ounces) of water and has a small tube, a straw, which is positioned next to the astronaut's mouth. Nutrition needs were partially accounted for in the EMU via inclusion of a modified commercial dried fruit bar that the astronaut could eat if he or she gets hungry during an EVA. The bars were labor intensive to make and were typically eaten prior to EVA or not at all, and were therefore discontinued years ago.

Potential methods for mitigating this contributing factor include shorter duration EVAs that preclude the need for substantial nutrition and hydration supplementation during the EVA. However, implementing shorter duration and more frequent EVAs could decrease overall work efficiency if the overhead associated with O₂ prebreathe and suit ingress/egress is not decreased. Alternately, the number of EVA hours could be reduced by employing pressurized roving vehicles and/or robotic assistants to complete some of the work that has been classically done only by EVA.

EVA suit design, task design, tool design, mission objectives, and exploration environment are all key factors in understanding the hydration and nutrition needs during EVA. The required mass/volume of food and water for EVA over a mission are directly associated with the required EVA hours. The caloric and hydration requirements per hour of EVA is directly associated with the physical demands of the work performed during the EVA. The physical demands of the EVA work are directly associated with the methods and equipment available to perform the tasks and the weight and mobility of the suit in which they must be performed.

The potential ramifications of not providing appropriate nutrition and hydration during EVA include the possibility of the need to shorten a planned long-duration EVA and possible loss of mission objectives. Also, health and performance issues may occur due to inadequate hydration or nutrition, within an EVA or over the length of a mission.

The longer and more work-intensive EVAs that are likely to be planned for future exploration missions will need to account for astronaut nutrition and hydration. Specifically, dehydration is an issue that can lead to poor crew performance. The Apollo suit had a 15-oz drink bag; however, this amount of fluid is considered insufficient for crews that are performing surface EVA. Scheuring et al. (Scheuring et al. 2007) describe several citations from Apollo-era astronauts who walked on the Moon regarding the need for more water. The authors wrote: "The astronauts strongly agreed the amount of liquid beverage contained in the suit needed to be increased for future crewmembers, including separate capabilities for plain water and non-caffeinated high-energy drink."

It was also recommended that the delivery systems for nutrition and hydration be improved as well. One Apollo astronaut commented: "The fruit bar mounted inside the suit was sometimes problematic because you couldn't always get to it, but it's nice to have something solid to eat" (Scheuring et al. 2007). Similar issues have been reported with the current EVA suit, used for microgravity EVA from the ISS. Furthermore, it was suggested that the time required to prepare the nutrition and hydration systems prior to conducting an EVA be decreased. Filling and degassing the drink bag used in the current U.S. suit is time-consuming and contributes to a poor work efficiency index (WEI) of shuttle and ISS EVAs.

The 10-km lunar walkback test also provided important insight into hydration and nutritional requirements for a worst-case task duration and intensity (Norcross et al. 2009). All subjects were provided an in-suit drink bag with 32 oz of water, the standard for use of the MK-III suit. Crewmembers consumed 50% to 100% of the water that was provided, and one crew member would have preferred to have an additional 20%. In addition, the 10-km walkback required an average of 944 kcal. All of the crewmembers felt that a nutritional item, either food (e.g. energy bar or gel) or a flavored electrolyte drink might improve their performance and/or endurance. These observations were in accordance with the Apollo recommendations cited above.

Additional background and evidence can be found in the NASA HRP Evidence Report “Risk Factor of Inadequate Nutrition” (Smith et al. 2015), “Evidence Report: Risk of Performance Decrement and Crew Illness Due to an Inadequate Food System” (Douglas et al. 2016) and “Human Adaptation to Space flight: The Role of Nutrition” (Smith et al. 2014).

IV.2. In-Suit Physical Environment

IV.2.1. Hypoxia

Hypoxia refers to low environmental oxygen conditions. Normally, 20.9% of the gas in the Earth’s atmosphere is oxygen. The partial pressure of oxygen in the standard atmosphere is 20.9% of the total barometric pressure. Atmospheric hypoxia occurs naturally at high altitudes. Total atmospheric pressure decreases as altitude increases, causing a lower partial pressure of oxygen, which is defined as hypobaric hypoxia. Oxygen remains at 20.9% of the total gas mixture, differing from hypoxic hypoxia, where the percentage of oxygen in the air is decreased. Other potential causes of hypoxia include medical causes such as pulmonary or respiratory disease or obstruction.

Unlike on Earth, habitable volumes in space are completely engineered environments, allowing the endless possibility of various atmospheric constituents. The ISS is set to a typical sea level atmosphere of 14.7 psia and 21% O₂. To ensure maximum mobility, EVA suits are kept at a low operating pressure, which is akin to increasing altitude in the Earth environment. To combat hypoxia and DCS, the suit environment is kept as close to 100% O₂ as possible with some N₂ remaining even after a 10-min purge with 100% O₂. This purge is required to remove the ambient ISS gas (21% O₂, 79% N₂) present in the suit during the suit donning process. In the engineered environment, hypoxia is best discussed as a partial pressure rather than altitude. Normoxia is an inspired partial pressure of O₂ (P_IO₂) of 150 mmHg calculated with the following equation:

$$P_{I}O_2 = P_B - 47 \times (F_{I}O_2)$$

With P_B defined as the total pressure in mmHg, 47 mmHg as the constant water vapor tension (P_{H2O}) in the human lung and F_IO₂ as the fraction of inspired O₂ in the ambient air.

At higher pressures, the P_{H2O} in the lung may be a small portion, but as the total pressure of the environment is significantly reduced, such as EVA, this constant P_{H2O} become a more significant factor. A lower suit pressure may improve mobility but increases the risk of both DCS and hypoxia. For further discussion on DCS, please see the NASA HRP Evidence Report “Risk of Decompression Sickness” (Conkin et al. 2016)

During the lunar missions, the Apollo A7L and A7LB suits were operated at 3.7 psia and 100% O₂, which results in a P_iO₂ of 144 mmHg, i.e. at the low end range of values considered physiologically normoxic. This level would be equivalent to an altitude of just under 1000 ft. The EMU operates at 4.3 psia and 100% O₂ resulting in a P_iO₂ of 175 mmHg. Assuming the suit can maintain adequate pressure and the life support system continues to deliver 100% O₂, hypoxia is a controlled factor for EVA risk.

Methods for mitigating hypoxia include design of the EVA suit so that it monitors and maintains appropriate breathing atmosphere pressures and oxygen concentrations under all expected EVA durations and human physiological demands. In addition, considerations should be made for contingency situations such as leaks or malfunctions that could compromise the breathing atmosphere within the suit. Current guidelines allow an EVA to continue as long as P_iO₂ is maintained above 127 mmHg (approximately 4000 ft equivalent altitude), but this is for contingency only and the nominal approach is to ensure a normoxic environment.

The ramification of not mitigating the risk of hypoxia during EVA include both health and performance impacts. These impacts include headache, decreased reaction time, impaired judgment, visual impairment, drowsiness, lightheadedness, lack of coordination, reduced oxygen delivery, and reduced muscle strength and power (Guyton and Hall 2000, Houston 2005).

IV.2.2. Hypercapnia

Hypercapnia is a condition of abnormally high carbon dioxide levels in the blood. Carbon dioxide is present in low concentrations (0.03%) in the standard atmosphere as well as being a gaseous product of the body's metabolism, and is normally expelled through the lungs during exhalation (Guyton and Hall 2000). Tolerance to inspired carbon dioxide varies as the concentration increases. Concentration levels between 1% and 5% may be able to be tolerated with mild to moderate effects (from mild respiratory stimulation to moderate respiratory stimulation with exaggerated respiratory response to exercise; increased heart rate and blood pressure, reduced hearing, dizziness, confusion, headache) for up to several hours at higher concentrations. Carbon dioxide levels above 5% elicit more prominent respiratory stimulation, exaggerated respiratory response to exercise, mental confusion, and dyspnea. Levels above 8% induce dimmed eyesight, sweating, tremors, unconsciousness, and eventual death (Lambertsen 1971) (Glatte Jr et al. 1967).

Methods by which hypercapnia might occur during EVA are by inadequate air flow within the suit causing "dead spaces" (or local concentrations) of carbon dioxide that are re-inhaled, or a failure in the suit life support system's ability to scrub excess carbon dioxide from the breathing air. Diving research has shown that hypercapnia can occur as a diver exhales into a vessel that does not allow all of the carbon dioxide to escape the environment, such as a full-face diving mask or diving helmet (Lamphier 1956) (2006).

EVA suits are expected to meet requirements for adequate carbon dioxide elimination (or "washout") to prevent significant re-inhalation. Spacesuit portable life support systems (PLSS) are also expected to meet requirements for adequate carbon dioxide removal. Sensors used on the

inlet and outlet for suit gas flow should serve to monitor and control levels of carbon dioxide. If the carbon dioxide level reaches a given criteria, then suit flow can be increased and/or activity level (thus affecting metabolic rate) of the crewmember can be reduced. If carbon dioxide levels cannot be improved and continue to rise over a critical threshold, the EVA can be terminated.

Higher than expected metabolic rates and/or faults in the carbon dioxide removal or ventilation capability of the PLSS would trigger elevated in suit carbon dioxide.

CO₂ washout studies have been conducted by the suit contractor and the NASA Johnson Space Center Crew and Thermal Systems Division (Chullen et al. 2013; Korona et al. 2014; Mitchell and Norcross 2012). These tests have been performed for several reasons, including evaluating ventilation configuration, characterizing the CO₂ washout within certain spacesuits, and ensuring safe ground based testing. Much of this work can be characterized as pilot studies that are helping to develop a standard method of assessing CO₂ washout performance in a spacesuit for ground based testing and eventually a CO₂ washout requirement verification for a flight EVA suit.

One of several concerns with these recent CO₂ washout studies is the use of an oronasal mask to fix the sampling locations. While the mask was comfortable to wear, it did extend off of the face and take up significant volume, especially noticeable in smaller helmets. There was also concern that the mask could affect the flow around the oronasal area and increase dead space. Due to these concerns, investigators looked into several options and settled upon the use of nasal cannula as the sampling location mechanism, but debate still remains about breathing style (nasal versus oronasal), methodology to analyze and interpret the in-suit data and then relate that data to terrestrial studies, which often use different standard approaches to quantifying CO₂ exposure (Meginnis et al. 2016).

To follow-up on these concerns, investigators have begun to define errors associated with the sampling technique and establish a standardized methodology for data analysis. Bekdash et al describe the necessary forward action to define a verifiable requirement for CO₂ exposure in EVA suits (Bekdash et al. 2017).

Of important note, throughout this series of CO₂ washout testing, subjects have exercised at metabolic rates up to 3000 BTU/hr at many different flow rates for several minutes and only rarely has a subject complained of CO₂ related symptoms while using the test termination criteria where the floor of the inspired CO₂ must remain below 30 mmHg at all times and cannot be over 23 mmHg for more than 2 minutes. Twice, both when the trial was terminated at a floor of 30 mmHg, did subjects complain of acute symptoms, but these symptoms resolved immediately by stopping the exercise that induced the high CO₂ levels. In many cases, during these studies, subjects have reported increased thermal stress and fatigue associated with the tested high suited metabolic rates, even when suited CO₂ levels were well within trial termination limits. This indicates that CO₂ is an important concern, but other factors also play a role. Once CO₂ washout performance is characterized on the ground and verified for flight, CO₂ in the suit will still need to be measured on both the inlet and outlet side during EVAs to ensure adequate CO₂ removal, as an index of CO₂ washout and to measure metabolic rate.

IV.2.3. Internal Suit Pressure

One of the primary functions of an EVA suit is to monitor and maintain a desired internal pressure. The internal pressure of a spacesuit must be adequate to maintain required breathing air partial pressures while the mobility and workload required to do tasks within the suit are kept at a reasonable level; it is a tradeoff of aspects of spacesuit operations that must be balanced (Abramov et al. 1994). The internal suit pressure used during EVA must also be tightly coordinated with the internal habitat or vehicle pressures to minimize the time required to transition from one environment to another. The negative pressure differences associated with moving from a habitat or vehicle to a spacesuit can cause decompression sickness, thus prebreathing higher concentrations of oxygen is required to reduce the risk of decompression sickness (Clément 2011). A detailed review of how NASA has mitigated DCS primarily through operational prebreathe protocols is discussed in the DCS risk Evidence Report (Conkin et al. 2016), but both DCS risk and prebreathe time can be reduced by the choice of optimal pressures and gas concentrations in both environments (Abercromby et al. 2013a) (Norcross et al. 2013a).

The current working assumption in the EVA community is that a lower suit pressure is better from a human performance and fatigue perspective. The main concern for operating the suit at a higher pressure is hand fatigue. Whole body tasks such as ambulation in the Mk-III did not show much difference in metabolic and subjective measures (Norcross et al. 2010b; Norcross et al. 2010d). Although higher suit pressures would significantly reduce prebreathe time, they are also associated with higher leak rates and greater suit mass to ensure needed structures.

IV.2.4. Hyper/Hypothermia

The physiologic cost of performing work in a pressure garment is significantly greater than that of performing the same work without a suit. High workloads result in energy expenditure and the production of heat, which, in turn, increase the usage rate of suit consumables. Flight surgeons must ensure that an astronaut is not working at levels that may lead to overheating or exhaustion, and EVA planners and/or crewmember may need to make real-time adjustments to crew activity to conserve consumables that are required for life support (Waligora and Horrigan 1975) (Waligora et al. 1975).

Energy expenditure (metabolic rate) was not measured during the Project Gemini EVAs. It was nonetheless clear that, in several cases, the astronauts worked at levels that were above the heat removal capability of the gas-cooled life support system (Kelley et al. 1968; Waligora and Horrigan 1975). During the first U.S. EVA, astronaut Ed White found that opening and closing the hatch was much more difficult than planned and that he perspired enough to fog the helmet visor. Although the duration of the EVA was short, it took several hours for White to return to thermal equilibrium (Paul 2012).

Thermal homeostasis of the crewmember is crucial for safe and effective EVA performance. Heat storage above 480 Btu/hour leads to performance decrements, such as a loss of tracking skills and increased errors in judgment, and tissue damage begins at 800 Btu heat storage (Jones et al. 2006). The observations from the Gemini experience led to the development of a liquid cooling system that could accommodate high heat production in the suit from high EVA workloads. This liquid cooling garment (LCG) consists of a system of plastic cooling tubes that

run along the inside of an undergarment that is worn inside the suit. The temperature of the coolant (water) running through the tubes regulates the amount of heat that is removed from the surface of the skin. The Apollo LCG had three temperature settings: minimum (69.8 °F/21 °C), intermediate (59 °F/15 °C), and maximum (44.6 °F/7 °C) (Waligora et al. 1975).

Astronaut energy expenditure rates during Apollo lunar surface EVAs ranged from 780 to 1,200 Btu/hr, as determined by three independent methods (Waligora et al. 1975). The lowest metabolic rates occurred while the astronauts drove and rode in the lunar rover vehicle, whereas the highest metabolic rates were observed during egress/ingress through the tight-fitting hatch of the lunar module, offloading and setup of equipment, drilling, and stowage of lunar samples. It is estimated that 60% to 80% of the heat that was generated with these workloads was dissipated through the LCG. The minimum and intermediate LCG settings were most commonly used; however, the maximum setting was frequently used during the high workload periods that were experienced during Apollo 15 and Apollo 17 EVAs (Waligora and Horrigan 1975). In a simulation (Figure 9) using a validated thermoregulatory model (Pisacane et al. 2007), the relationship between heat storage and metabolic rate was examined as a function of LCG inlet temperature (tracings, showing 21 °C (69.8 °F) & 24 °C (75.2 °F)) (Thomas et al. 2011). These data suggest that at metabolic rates above ~1200 Btu/hour, LCG inlet temperatures exceeding 21 °C may induce crewmember heat storage rates above the 480 Btu/hour that lead to performance impairment. Although Apollo metabolic rates rarely exceeded 1200 BTU/hour and the LCG inlet temperature minimal setting was 21 °C, this data is instructive for the design of future EVA suits, which may be used in situations in which crew metabolic rates exceed levels seen during Apollo.

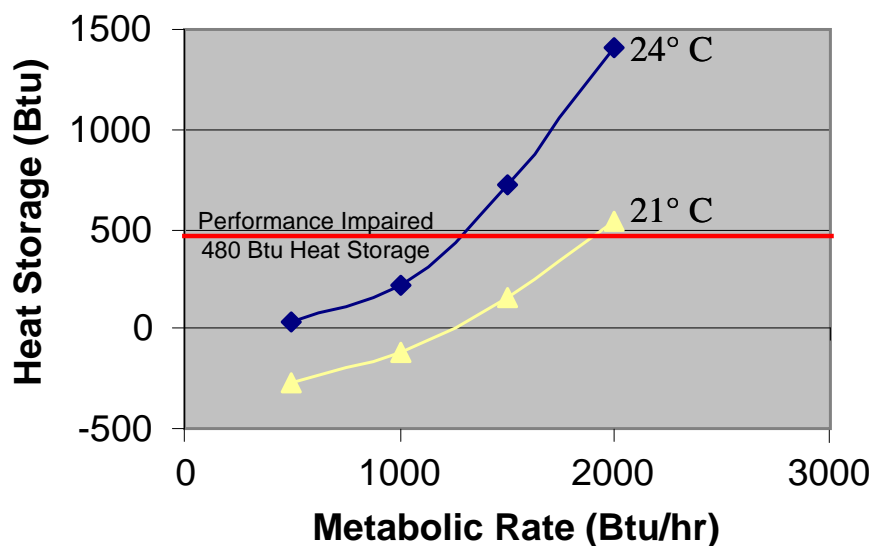


Figure 9 - Heat storage based on metabolic rate and LCG inlet water temperature. (Pisacane et al. 2007)

During NASA's Constellation Program, a study was conducted to determine whether it is possible for a suited crewmember to walk back to a terrestrial habitat in the event of a failed rover (Norcross et al. 2009). As a starting point that is based on the Apollo Program and anticipated lunar surface operational concepts, it was assumed that 10 km (6.2 miles) would be the maximum EVA excursion distance from the lander or habitat. Results from this EVA EWT

using the POGO partial gravity offload system provide key insight into how human performance may be impaired by inadequate consumables and/or inadequate cooling.

For the EWT, 6 suited subjects were instructed to attempt to translate 10 km (6.2 miles) on a level treadmill at a rapid, but sustainable, pace using a self-selected gait strategy and speed. Prior to this test, the investigators expected that crewmembers could only complete half of that distance or that the total duration would exceed 3 hours. However, all of the crewmembers finished the test, and the mean time to complete 10 km was only 96 minutes. The metabolic work level for the entire test averaged 51% of $\text{VO}_{2\text{pk}}$, with a range of 45% to 61%. Physiological and consumables usage data are summarized in Table 1. RPEs (11.8 ± 1.57 (standard deviation (SD))) equated to a feeling between “light” (RPE=11) and “somewhat hard” (RPE=13) on the 6-20 point Borg RPE scale, which is used to gauge how much effort a person feels that he or she must exert to perform a task. Similarly, subjects averaged 3.5 ± 1.44 (SD) on the 10-point GCPS, indicating “fair” to “moderate” operator compensation was required to perform the task (Norcross et al. 2009).

Subjects’ heat production rates ranged from 1,918 to 2,667 Btu/hour, and averaged 2,374 Btu/hour; a rate that would exceed the heat removal rates of the Apollo EVA suit or current EMU. Core temperature measurements indicated an average rise (Δ) of 1 °C from normal (98.6 °F/37 °C) across the entire test, although one subject’s core temperature (103.6 °F/39.8 °C) peaked near a level of concern. Subjects unanimously reported cooling to be inadequate at the higher workloads (Norcross et al. 2009).

This limited cooling capacity will impede the improved efficiency that was observed at higher speeds. Efficiency of locomotion can be determined by the transport cost, which is expressed as oxygen consumption per kilogram per kilometer, and can be thought of as a human’s “gas mileage.” In suited conditions in lunar gravity, there was a clear trend of decreasing transport cost as speed increased. So while a crewmember might expend more energy on a per minute basis by traveling at faster speeds, the metabolic cost per kilometer would actually be less (Norcross et al. 2009).

Table 1 - Summary data for the lunar 10-km Walkback test (Norcross et al. 2009).

10k Walkback (averaged across entire 10 km unless noted)	Summary Data	
	MEAN	SD
Avg. Walkback Velocity (mph)	3.9	0.5
Time to Complete 10 km (min)	95.8	13.0
Avg. % $\text{VO}_{2\text{pk}}$	50.8%	0.3%
Avg. Absolute VO_2 (l/min)	2.0	0.3
Avg. Metabolic Rate (Btu/hour)	2,374.0	303.9
Max. 15-min-avg Metabolic Rate (Btu/hour)	2,617.2	314.6
Total Energy Expenditure (kcal)	944.2	70.5
Water used for drinking (oz.)	~24–32	N/A
*Water used for cooling (lb.)	4.91	N/A
Oxygen Used (lb)	0.635	N/A
Planning/PLSS Sizing Data	Walkback	Apollo

Oxygen Usage (lb/hour)	0.4	0.15
Btu Average (Btu/hour)	2,374	932.8
Cooling Water (lb/hour)	3.1	0.98
Energy Expenditure (kcal/hour)	599	233

*Assumes thermally neutral case and sublimator cooling

Unfortunately, at speeds above 3 mph (Figure 10) the heat production, which is shown on the right axis and the red tracing, begins to exceed the 2,000 Btu/hour cooling limit of both the Apollo and the EMU EVA suits, resulting in increased core body heat storage. Without improvements in cooling for future suits, crewmembers performing lunar EVAs would not be able to exploit the increased efficiency (Figure 10, on the blue tracing as decreasing oxygen transport cost) available at faster ambulation speeds. This would result in increased consumable requirements to cover the same distance (Norcross et al. 2009).

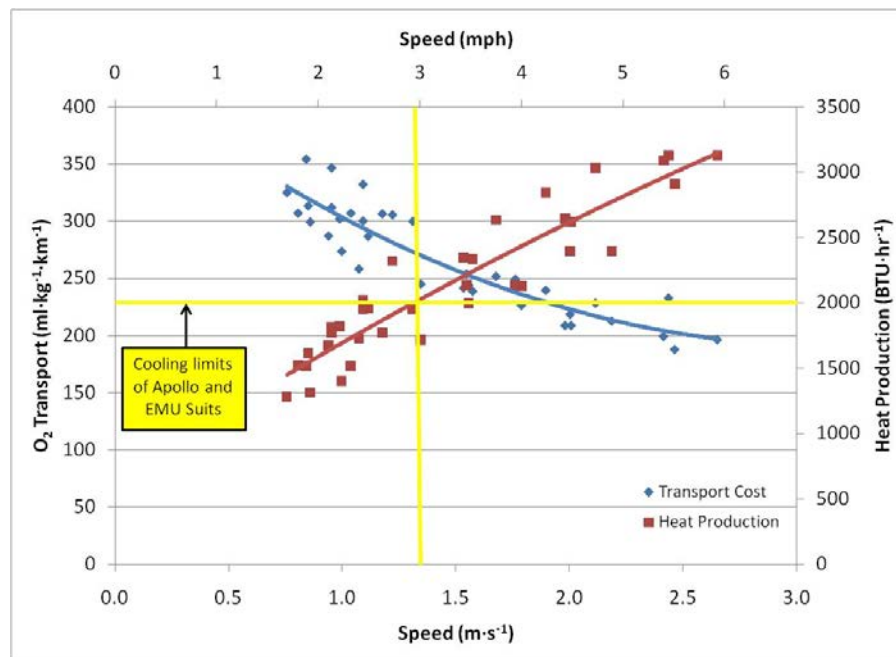


Figure 10 - Relationship between transport cost and heat production for lunar suited ambulation. (Norcross et al. 2009)

IV.2.5. Humidity

Humans perspire and exhale molecular water. In a closed environment such as a spacesuit, this quickly causes extremely humid conditions that not only cause discomfort, but can also adversely affect the function of systems within the spacesuit. Thus, a spacesuit system must remove humidity. But removal of the humidity in the ventilation system can cause yet further difficulties. An atmosphere that is too dry can adversely affect the eyes and nasal passages of the suit user. Over 8-hour periods and repeated usage, this can affect the mission and the well-being of the astronaut. An excessively dry atmosphere can also result in hazards from electrostatic discharge. Should a static electricity discharge occur within a spacesuit, it could involve tens of thousands of volts, but only microamps of current. This could shock, but not harm, the

crewmember. However, as this could damage sensitive electronic components, suit systems must remove excess humidity while maintaining at least minimum levels of humidity for both comfort and safety (Thomas and McMann 2011).

Problems have been reported with excess moisture in suit causing face plate fogging (Paul 2012). In addition, excess humidity may be a factor in finger nail delamination during EVA (Jones et al. 2008). Excess moisture in a spacesuit may be associated with increased heat loads of EVA crew as high levels of humidity do not allow for sweating to be effective at cooling the body, which may lead to excessive sweating and eventual dehydration. Addressing this contributing factor may result in less risk to crew health and performance by reducing the hand injuries from EVA and better management of carried heat load.

IV.2.6. Radiation Exposure

An astronaut performing EVA is exposed to radiation whether on a planetary surface or in deep space. Being close to a planetary body can provide some shielding but the EVA suit becomes the only method of protection in deep space (Committee on the Evaluation of Radiation Shielding for Space Exploration 2008). Considering an entire mission, not just the EVA portions, the current space radiation permissible exposure limits (PEL) limits mission duration to 3–10 months depending on age, gender and stage of the solar cycle (Steinberg et al. 2013). During EVA, the protection that a spacesuit provides is minimal and thus the length of exposure becomes a factor in managing radiation risks. As an example, EVA helmets have been shown to only produce a 13% to 27% reduction in radiation dose to the head as compared to a non-helmeted head; similar minimal protection has been shown for the torso and extremities (Benton et al. 2006). Thus, monitoring of solar activity in real-time and providing predictions and alerts for high radiation events is important in planning and scheduling of EVAs (Johnson et al. 2005). Rovers and/or habitats can be designed with water or other materials in the walls and ceilings to provide good radiation protection to crewmembers inside. In addition, the capability to rapidly egress and ingress a habitat or rover can significantly reduce the chances of excessive radiation exposure because shielded areas can be accessed faster (Abercromby et al. 2012b).

Additional background and evidence can be found in the NASA HRP Evidence Report: Risk of Acute (In-flight) or Late Central Nervous System Effects from Radiation Exposure (Nelson et al 2016), “Risk of Acute Radiation Syndromes Due to Solar Particle Events” (Wu et al. 2013) and other radiation-related reports.

IV.2.7. Decompression Sickness

When a diver returns from a hyperbaric environment, or an aviator or astronaut travels to a hypobaric environment, inert gas in excess of what can be held in solution at the new lower pressure has the potential to come out of solution and form gas spaces that can displace or otherwise damage tissues. Unlike other space flight related human risks, DCS is a known problem that has been mitigated since the first EVA. Various DCS mitigation strategies have effectively been used including a lower pressure high oxygen environment (Gemini, Apollo, Skylab) requiring a single 4-hr pre-launch oxygen prebreathe (PB); a resting 4-hr in-suit PB; an intermediate pressure, mildly hypoxic environment requiring a single 40- to 75-min in-suit PB; and several exercise-enhanced protocols combining both mask and in-suit PB. To date, DCS has been effectively mitigated through rigorous adherence to PB protocols validated specific to the

EVA environment and primarily to the microgravity (μ G) environment. While effective, these protocols can be complex and require significant pre-flight training, in-flight crew time and consumables usage.

Historically, prebreathe protocols have been developed with the goal of preventing DCS and have been designed to meet operational needs. This operationally driven research has left gaps in knowledge about several DCS risk factors including bubble formation in space, nitrogen elimination in space, break in PB, micronuclei generation and tissue saturation across different pressure and gas environments.

The acceptable risk for DCS has been defined in the NASA Human Space flight Standards, therefore, the next step will be to develop and validate procedures, protocols, and countermeasures to meet this standard effectively and efficiently for the range of nominal and off-nominal atmospheres and decompression profiles that crewmembers may experience during future exploration missions. Utilization of the Exploration Atmosphere (8.2 psia / 34% O₂), suit ports, variable pressure suits, and the inability to rapidly deorbit for medical treatment mean that existing DCS risk mitigation protocols and data sets are not applicable to future exploration missions.

To improve efficiency from a sea level atmosphere, data is needed on the potential differences in bubble formation and N₂ elimination while in μ G. To improve safety and efficiency from any atmosphere, data is needed to describe the consequences of a break in PB. Finally, the opportunity exists to mitigate DCS primarily through engineering controls by the use of the 8.2 psia / 34% O₂ Exploration Atmosphere, suit port and variable pressure EVA suit. While promising, this strategy still requires validation to ensure it mitigates DCS risk to acceptable levels and to determine if there are any significant negative physiological effects associated with the Exploration Atmosphere's mild hypoxia of approximately 4000-ft equivalent altitude (Conkin et al. 2016).

IV.2.8. Ebullism

An astronaut performing EVA is exposed to the risk of rapid decompression due to a suit system failure. One of the effects of rapid decompression is ebullism. Ebullism is a condition where ambient pressure is \leq the vapor pressure of water, 47 mmHg at a body core temperature of 37°C, and where liquid water undergoes a phase transition to vapor. This condition is conceptualized as low-temperature boiling of water.

The transition from liquid water to water vapor partial pressure at 47 mmHg (37°C) in aviation medicine is termed the Armstrong's line, or limit (Murray et al. 2013). It represents a potentially fatal depressurization, equivalent to exposure above an altitude of 19,200 m (63,000 ft). Loss of aircraft cabin pressurization above 19,200 m without a protective pressure suit or depressurization of a spacesuit to near-vacuum conditions in space or in an altitude chamber results in ebullism. This is a rare event; two brief descriptions are provided by Stepanek (Stepanek 2002).

Except in cases when extremely rapid repressurization is administered within about one minute of the event, it is unlikely that ebullism is survivable due to limited treatment resources at

the time of the event and time required to establish resuscitation. For example, liquid water contained in lung tissues would immediately vaporize and fill the alveolar space, displacing all other gases as all gases simultaneously exit the lung to establish pressure equilibrium at the new low ambient pressure. Since the lung cannot contain the expanding volume, gases leave the lung while the corresponding partial pressures, particularly O₂, decrease precipitously. If unchecked, then anoxia and death ensue before evolved gas bubbles have the time to damage tissues.

It may be possible to survive ebullism induced by loss of suit pressure during high-altitude bailout, such as was performed during the Red Bull Stratos Mission in 2012. In this case there was no loss of pressure during the mission, but the medical team reviewed available literature and developed a treatment protocol for ebullism (Murray et al. 2013).

Mitigating factors for ebullism in relation to EVA include the design of the EVA suit systems to resist puncture or rupture under expected operational conditions, as was done with the Integrated Thermal Micrometeoroid Garment during the Apollo lunar surface missions (Thomas and McMann 2011).

IV.2.9. Embolism

Decompression sickness is associated with gas embolism (the presence of gas bubbles in the vascular system), both venous gas emboli (VGE) and arterial gas emboli (AGE). Although VGE can typically be adequately filtered by the lung, circulating VGE is not a desired condition, especially with the presence of a patent foramen ovale (PFO), which is a hole in the wall separating the right and left atria of the heart. A PFO is a remnant of life in the womb where oxygenated blood from the placental circulation is shunted away from the pulmonary circulation of the fetus. This connection closes in most newborns, but about 25% of the adult population has some small patency (hole) that allows oxygenated and deoxygenated blood to mix. If denitrogenation is not effective, either due to inadequate vehicle design (either in gas constituency or atmospheric pressure, or a combination of both) or inadequate operational PB protocols, then the resulting presence of VGE during an EVA could cross through a patent PFO under particular conditions and become arterialized. AGE put the astronaut at risk of vascular blockages and resulting ischemic damage to brain or other organs (Conkin et al. 2016).

IV.3. EVA Factors

IV.3.1. Work Efficiency Index

Current EVA suits and systems have a significant amount of overhead as compared to productive time on EVA. The work efficiency index (WEI) is a method of quantifying productivity and comparing different EVA methods/systems. WEI for EVA is calculated as follows:

$$Total\ EVA\ WEI = \frac{Total\ EVA\ Time}{Total\ EVA\ Overhead\ Time}$$

EVAs during the Apollo missions averaged a work efficiency index of approximately 2 with EVA durations of about 7 hours (Walz and Gernhardt 2008). As new spacesuits, namely the current EMU, became operational they worked in conjunction with the Space Shuttle and the ISS

to provide an EVA capability in low Earth orbit. A number of factors, including standard atmospheric pressure (760 mmHg / 14.7 psia) as the baseline conditions in both the Space Shuttle and ISS as compared to the design operating pressure of the EMU (222 mmHg / 4.3 psia), caused the EVA WEI to decrease to approximately 0.4. Differences in the operating pressure of the vehicles and suit require a long oxygen prebreathe to minimize the risk of decompression sickness; this along with other factors causes EVA preparation to take as long as 5-6 hours (Norcross et al. 2013b). Comparatively, commercial saturation diving achieves a WEI of between 3 and 10 through the use of synergistically designed habitats, vehicles, and diving suits that together enable much lower overhead time (Cooke et al. 2007). A comprehensive assessment of operational and engineering design for future EVA systems (i.e. suits, habitats, and vehicles) indicates that EVA WEIs of up to 9 should be achievable (Cooke et al. 2007). The first step toward this new operational and design approach has included the decision to use a 8.2 psia / 34% oxygen exploration atmosphere baseline in the exploration vehicle, which will significantly decrease the time required for prebreathe and thus reduce overhead time (Norcross et al. 2013a). Improvements in EVA system design could also produce major improvements in EVA WEI: such as improved biomedical sensors, shorter suit checkout and servicing times, efficient egress/ingress times from vehicles/habitats, and decreased suit don/doff times

IV.3.2. EVA Task and Timeline Design

EVA task and timeline design is important to human health and performance. EVA task design refers to the particular equipment and methods used to perform necessary mission EVA tasks. EVA timeline design refers to the detailed analysis and testing that is required to understand the necessary duration and sequencing of tasks and subtasks within a particular EVA or set of EVAs in order to achieve overall objectives. If EVA tasks or timelines are not developed with human health and performance as a factor in their design, there is a risk that injury or reduced performance may occur along with possible loss of mission objectives.

Currently, very little is defined in standards that govern NASA human space flight regarding operations that would serve to provide requirements for the design of effective, efficient, and safe EVA tasks and timelines (NASA 2007; NASA 2011a). However, analog research performed by the EAMD team has introduced a model of early human testing of prototype systems that can factor in human health and performance concepts of operations and system design as early as possible. Before the NEEMO 14 mission, the EAMD team performed extensive task and time analysis of important lunar surface EVAs, which informed the design of the research study to validate and collect metrics on different tasks and timelines (Chappell et al. 2011). Similar processes were used before and during NASA's Research and Technology Studies (RATS) missions from 2008-2012 (Abercromby and Gernhardt Manuscript submitted for publication; Abercromby et al. 2010; Abercromby et al. 2013b; Abercromby et al. 2012a; Abercromby et al. 2012b), which tested both planetary surface and Near-Earth asteroid missions. Near-Earth asteroid mission task analysis and timeline validation was also assessed during NEEMO 15 and 16 (Chappell et al. 2013a; Chappell et al. 2013b).

Finally, it is possible to use the results of task and timeline testing to make projections of the human health and performance impacts of operations and inform the need for countermeasures to combat muscle and bone loss. The report "Life Science Implications of Lunar Surface Operations" used objective data from analog and integrated suit testing to model a day-in-the-life

of an EVA crewmember on potential lunar missions (Chappell et al. 2010b); similar modeling could be enabled by future research that is geared toward other destination environments.

The NASA analog and integrated testing program has proven to be a cost effective and essential method to ensure that end-user health and performance are central to future human task and timeline design (Reagan et al. 2012).

Additional background and evidence can be found in the NASA HRP “Evidence Report: Risk of Inadequate Critical Task Design” (Sandor et al. 2013).

In addition to optimizing EVA operations, task related risks can be identified to reduce injury rates caused during EVA or EVA training time. Repetitive motion causes injury if too much time is spent in certain positions that cause fatigue or injury, and this can lead to a failed task or decrease in performance. As much as is possible, tasks and procedures should be designed to avoid extended time in one position and to divide up the time spent in uncomfortable positions. For example, crewmembers can experience pain if they spend too much time working with arms overhead (a non-optimal position with the current EMU scye bearing). Working at an angle can also cause problems as it may result in the crewmember placing their body into a suboptimal position. Inverted time in the NBL is now managed operationally by monitoring and restricting both for the acute exposure and the cumulative exposure over a training session.

IV.3.3. EVA Resources

The EVA resources contributing factor refers to the necessity of monitoring and management of EVA systems, plans vs. actuals, consumables, etc., to help ensure the health and performance of crewmembers. For instance, the physiologic cost of performing work in a pressure garment is significantly greater than that of performing the same work without a suit. High workloads result in energy expenditure and the production of heat, which, in turn, increase the usage rate of suit consumables. Accordingly, monitoring of crew physiologic parameters and consumables is critical. Flight surgeons must ensure that an astronaut is not working at levels that may lead to overheating or exhaustion, and EVA planners must be able to make real-time adjustments to crew activity to conserve consumables that are required for life support (Waligora et al. 1975; Waligora and Horrigan 1975).

It is important to note that although the metabolic rates experienced during the Apollo EVAs were lower than had been predicted before the missions, there were several cases in which the PLSS consumables were nearly depleted, according to the *Summary of Apollo G Mission Lunar Surface EMU Post Flight Thermal Analysis Results, Table E1* (Mission Operations Directorate (MOD), unpublished internal report). During Apollo 14, Apollo 15, and Apollo 17, there were 6 cases in which less than 10% usable oxygen remained at the end of the EVAs. During Apollo 14, Apollo 16, and Apollo 17, there were 7 cases in which 12% or less power remained (in one case, power was at < 4%), and 4 cases in which 11% or less usable feed water remained. Two crewmembers, on Apollo 15 and Apollo 16, completed their EVAs with only 4% and 2% remaining, respectively, of their CO₂ removal capability (lithium hydroxide (LiOH)).

Although each of the Apollo missions was limited to 2 or 3 EVAs, future missions may consist of multiple EVAs per week for up to 6 months. The increased number and frequency of

exploration EVAs, coupled with labor intensive construction and exploration tasks, will require a better understanding of energy requirements, heat dissipation technologies, and consumables management.

Flight surgeons and biomedical engineers (BMEs) in the Mission Control Center monitor astronaut physical parameters during EVAs to assess workload and performance. Real-time medical monitoring can provide emergency medical assistance in response to off-nominal situations. However, bioinstrumentation systems that were used in the Apollo Program and are being used in the Space Shuttle Program have been problematic. Scheuring et al. (2007) provide approximately 75 citations from the flight surgeon logs, BME logs, and medical mission debriefings that relate to issues associated with bioinstrumentation. These range from complaints of skin irritation due to the electrode paste to signal dropouts and sensor failure (Scheuring et al., 2007). Both Apollo and shuttle/ISS EVA crewmembers have expressed frustration with the cumbersome and time-consuming process of donning/doffing their biomedical sensor systems. Improvements to the biomedical sensor systems for future missions are therefore warranted.

More detailed background and evidence can be found in the NASA HRP “Evidence Report: Risk of Inadequate Human-Computer Interaction” (Holden et al. 2013).

IV.3.4. EVA Environment

IV.3.4.1. Background/significance specific to the contributing factor

The EVA environment in which crewmembers must perform is dependent on the destinations chosen for human exploration. Planetary destinations present inherent, unchangeable factors that must be dealt with, such as sloped and/or extreme terrain, zero or partial gravity, and dust. The EVA systems may not be designed to mitigate the effects on human health and performance of these factors without appropriate research to address them.

Slope

The effect of slope on the mechanics and metabolic cost of locomotion has been extensively studied (Minetti et al. 2002). However, the combined effect of partial gravity and sloped terrain has a more limited research base. The human health and performance effects of factors such as sloped terrain on an EVA crewmember were studied during integrated suit testing. Sloped terrains of 10-30% grade were shown to have a substantial impact on metabolic load required to ambulate in a spacesuit (Norcross et al. 2010b). Another study evaluated boot design for gradients up to 32 degrees (Hodgson et al. 2000).

Specific studies targeting the effects of slope have shown that internal work has no role in determining the optimal gradient (Minetti et al. 1994). It has been theorized that the different efficiencies of the muscles explain the metabolic optimum gradient for running of about -10%. Additionally, gradients as low as +15% induce about 2.5 times higher metabolic costs than the optimum low cost of slight downhill running (Minetti et al. 1994). In other studies, electromyography has shown that uphill running activates more of the lower extremity muscles than does horizontal running through an altered pattern of muscle activation (Sloniger et al. 1997). It has been hypothesized that uphill movement allows for less storage of elastic energy and thus is less efficient. Also theorized is that differences in posture change the orientation of

the ground reaction force vector, and thus the mechanical advantage of muscles and tendons when ascending hills (Chang and Kram 1999).

Military scientists have proposed models for load carriage on sloped terrain. Results from these models have determined that the total work for uphill walking can be calculated from the baseline value for walking (with and without load) by adding a term for positive external work against gravity (Santee et al. 2001). For downhill load carriage, the force applied through the body is modified, not by muscle inefficiency, but by a combination of energy absorption into the joints and within the muscles. Any reduction in the energy cost of downhill walking due to the negative work of gravity being offset or reduced by eccentric work within the muscles, some additional energy absorption by the muscles and joints, and voluntary braking action to slow or control descent. The minimum value for VO_2 was induced during walking and running a downhill grade of -8% (Santee et al. 2001).

Overall, little attention has been paid to studying the cost of locomotion at high-angle slopes. A single study has shown that the optimum gradient for mountain paths is close to 0.2-0.3, both uphill and downhill (Minetti et al. 2002). This study shows that the running speeds adopted in downhill competition are far lower than metabolically feasible, mainly because of safety reasons. Athletes back off on speed to minimize joint and tissue injury. Also, at high angles, the body's center of mass (COM) accelerates down the hill rather than being a controlled constant braking. This may result in a lack of the fine motor control needed to maintain body trajectory on rough and slippery terrain (Minetti et al. 2002). These effects are likely to be amplified in reduced gravity environments, but no research performed to date in this area could be found in the literature.

Surface Properties

Some studies have been performed to examine the effects of surface properties on locomotion and associated metabolic cost. There are major differences in the energy expended dependent on the surface properties. For instance, it has been determined that walking on sand requires 1.6-2.5 times more mechanical work than does walking on a hard surface at the same speed (Legeune et al. 1998). In contrast, running on sand only requires 1.15 times more mechanical work than does running on a hard surface at the same speed. The increase in energy expenditure is due primarily to two effects: the mechanical work done on the sand; and a decrease in the efficiency of positive work done by the muscles and tendons (Legeune et al. 1998). These effects are likely to be amplified in a reduced gravity environment such as the Moon and Mars, as implied by the aforementioned stability concerns. Also, the environment on the surface of the Moon and Mars consists of sand, loose soil, and scree field in many regions of scientific interest (Eckhart 1999).

Surface properties were considered a significant factor for differences observed in a speed and grade matched shirt-sleeve 10-km walkback on Devon Island and a treadmill control. Although the average 1-min speed and grade were matched more than 98% of the time on the treadmill, the treadmill testing did not fully simulate the demands of traversing extreme terrain and underestimated the demand by about 56% (Norcross et al. 2008). This research clearly showed the necessity of both lab-based and field-based testing to understand the effects of terrain

and slope on EVA operations. Future EVA simulations need to consider the combined effects of performing EVA tasks in both reduced gravity and loose substrates.

Reduced Gravity

Most of what is known about EVA performance and injury rates is derived from a combination of the flight microgravity environment data and the NBL microgravity simulation data. This data is also limited to the EMU. Extending this work to partial-gravity EVA is critical but difficult to accomplish.

The effects of reduced gravity on EVA crewmember health and performance have been studied via various methods (i.e. underwater (Trout and Bruchey 1969), parabolic flight aircraft (Moran 1969), weigh offload systems (Sanborn et al. 1967; Wortz and Prescott 1966); (De Witt et al. 2014; Robertson and Wortz 1968; Wortz 1969) De Witt et al. 2014]) since the days before the Apollo moon landings. Limited data was collected during Integrated Suit Test 1 and 2 that included level and inclined ambulation as well as a set of core exploration tasks. However, the POGO system used during that test was not able to provide enough weight offload to properly simulate both the weight and mass of suits in different gravitational environments. Therefore, metabolic, biomechanical, and other data needs to be validated with true weight/mass matching on a more capable system such as ARGOS. Additionally, data was only collected using the Mk-III suit and the effects of other suits on health and performance are not understood.

IV.3.5. Quality of EVA Procedures

Procedural guidance for EVA can be a contributing risk factor when written direction, checklists, or procedures are inadequate. Because procedures drive virtually every space flight task, the probability of poor procedural guidance causing an incident is high. For long-duration missions, there will be an even longer delay between training and task performance – increasing the level of reliance on procedures. In addition, ground personnel may not be available to interpret/rework poorly written procedures during time-critical events (Love and Reagan 2013; Sandor et al. 2013).

The cost of adequate procedure design is minimal compared to the cost of lost mission objectives or a severe incident due to poorly written procedures. If procedures are inadequate, crewmembers will ask for help from another crewmember or from ground support; this may lead to delays in task completion and the need for complex and costly schedule changes. Alternatively, crewmembers may proceed on without help (taking their best guess), increasing the potential for improperly executed tasks leading to errors and missed mission objectives.

More detailed background and evidence can be found in the NASA HRP “Evidence Report: Risk of Inadequate Critical Task Design” (Sandor et al. 2013).

IV.3.6. EVA Training Inadequacy

EVA training issues can become a contributing risk factor when necessary training programs are inadequate or unavailable. There is a high likelihood of minor time losses and inefficiencies and a small, but non-zero, likelihood of serious damage to space systems due to errors resulting from inadequate training. Generally, the likelihood of issues may increase with increased mission duration and crew autonomy. In some cases, training programs may be inadequate because they

do not result in appropriately generalizable skills. Additional risk factors (fatigue, stress, excessive workload) can significantly alter the conditions of task performance relative to those during task training, and this can lead to decrements in performance. In addition, the passage of time and the lack of opportunity to rehearse or refresh acquired knowledge or skills can result in performance declines, reflecting a lack of recollection of what was learned. Training programs that do not account for degradation of learned skills or knowledge (e.g., by including refresher training or by providing just-in-time training rather than advance training on the ground) may result in inferior task performance. A further complication arises as a result of the novel technologies and operational scenarios that may exist for deep space missions.

More detailed background and evidence can be found in the NASA HRP “Evidence Report: Risk of Performance Errors Due to Training Deficiencies” (Barshi 2016).

IV.3.7. EVA Crew Collaboration

Coordination and autonomy aspects of EVA will need to be addressed to optimize task performance, psychosocial performance, and teamwork during long duration missions. No formal procedure to handle coordination issues currently exists. Within the current hierarchy of the crew, it is assumed that the commander will make any final decisions. Multiple incidents of a lack of coordination between flight crew or flight and ground crews have occurred. Environment constraints, including communication delays and isolated, confined, and extreme environments over a long duration may impact issues related to crew collaboration over time. Crews may have to make decisions independent of ground control when presented with novel tasks in time critical situations, and consideration will need to be taken for the functional allocation of crewmembers (and skillsets) within the work domain (Feigh and Pritchett 2014). Understanding how teams can effectively coordinate and collaborate to accomplish the tasks and objectives set before them is imperative; the ability to complete what is required of them as a team is even more difficult when considering the context of a long duration mission, and thus it is essential that research identifies the most effective mitigation strategies to address this contributing factor.

More detailed background and evidence can be found in the NASA HRP Evidence Book: “Risk of Performance and Behavioral Health Decrements Due to Inadequate Cooperation, Coordination, Communication, and Psychosocial Adaptation within a Team” (Landon 2016), and in “Risk of performance errors due to poor team cohesion and performance, inadequate selection/team composition, inadequate training, and poor psychosocial adaptation” (Schmidt et al 2009).

IV.4. Physical State

IV.4.1. Crewmember Physical Preparation

The long transit times in 0-g for exploration missions could cause decreases in muscle strength, power, and endurance as well as aerobic capacity that might impact the crew’s ability to perform EVA tasks. This risk could potentially be prevented or mitigated by selecting astronauts that have higher baseline fitness/strength levels. Exercise countermeasures are used to mitigate other risks but their effectiveness is unknown in relation to future exploration EVA operations.

The Functional Task Test (FTT) was recently completed to assess crewmember physical preparation and recovery following return to Earth (Bloomberg et al. 2016). This study provides the most comprehensive analysis of post-flight physiological readaptation to date, but some gaps in knowledge remain. The Field Test is a follow-on to the FTT which looks at a select number of simple performance tests that can be administered in the field immediately post landing (Reschke et al. 2016). These studies provide valuable data that will contribute to discussions and future studies that will determine when nominal EVA operations can begin on Mars as well as the potential off-nominal or limited EVA capabilities that might be available post landing on Mars.

In addition to determining when and what tasks a crewmember could perform for the first EVAs on Mars, there is also a need for fitness for duty standards for EVA. Current standards do exist, but are not well defined (NASA 2007). This effort to define fitness for duty standards is the focus of the Fitness for Mission Tasks (FMT) studies (English et al. 2017). To fill in the gaps for EVA-like task timeline and energy expenditure profiles, the FMT studies will coordinate with the EVA HH&P Benchmarking Study, ultimately leading toward a suited validation study of fitness for duty standards (Abercromby et al. 2016). Beyond fitness for duty standards, there is also a requirement to evaluate the crewmember's physical readiness prior to an EVA. On ISS, a pre-EVA health check with ground concurrence is required before a crewmember begins an EVA, but the effectiveness of this process will be difficult to implement for missions with time delay, possibly necessitating a crewmember-based method of assessing readiness on the day of EVA.

IV.4.1.1. Decreased Muscle Power, Decreased Muscle Strength, Decreased Muscle Endurance

Exercise countermeasures will be a part of any exploration program and future research to develop maximally effective countermeasures to protect muscle power, strength and endurance will help to ensure mission success and the safety of crewmembers. Mission architectures, EVA surface suits and systems, and EVA task plans need to consider the potential limitations of crewmembers after long duration transits in 0-g and partial gravity destination. Additional research is needed to understand if current standards are appropriate to help ensure EVA mission objectives can be achieved with acceptable levels of injury to crewmembers.

More detailed background and evidence can be found in the NASA HRP "Evidence Book: Risk of Impaired Performance Due to Reduced Muscle Mass, Strength, and Endurance" (Ploutz-Snyder et al 2016).

IV.4.1.2. Decreased Mobility Due to Vestibular/Sensorimotor Alterations Associated with Space flight

Given there is an alteration in vestibular/sensorimotor function during and immediately following gravitational transitions, which manifests as changes in eye-head-hand control, postural and/or locomotor ability, gaze function, and perception, it is possible that crews will experience decreased mobility during EVA on a planetary surface after long-duration space flight.

More detailed background and evidence can be found in the Evidence Report: “Risk of Impaired Control of Spacecraft/Associated Systems and Decreased Mobility Due to Vestibular/Sensorimotor Alterations Associated with Space flight” (Bloomberg 2016) and in “Risk of sensory-motor performance failures affecting vehicle control during space missions: a review of the evidence.” (Paloski et al. 2008).

IV.4.2. Pre-Existing Injury or Illness

Depending on severity, pre-existing injuries or illness can have significant effects on EVA performance. If a crewmember sustains an arm injury that causes pain that results in disuse, there will likely be impacts on mission objectives (Viegas et al. 2004). In addition, treatment of injury or illness could delay mission objectives or prevent completion of mission objectives. Possible mitigations for this risk include cross-training crewmembers on EVA activities, thus providing a backup. Private medical conferences (PMCs) with the flight surgeon (NASA 2007) and/or a pre-EVA checklist of physical capabilities can also mitigate the risk. If a pre-check shows that the astronaut could not complete an EVA, then workarounds will be necessary. Finally, the amount of time spent on EVA during long-duration exploration can be reduced by employing robotic systems when possible (Hörz et al. 2013).

IV.4.3. Fatigue

According to the Apollo lunar crews, the most fatiguing part of surface EVA tasks was repetitive gripping. Regarding the glove, one crewmember stated, “*Efficiency was no more than 10% of the use of the hand.*” It is also interesting to note that the lunar crews stated that they did not experience hand or forearm trauma in training, though muscle fatigue occurred. However, these training sessions typically lasted only 2 to 3 hours, whereas the lunar EVA’s including pressurized prep time were 7 to 9 hours. Recent experience with ISS-related EVA’s suggests that better conditioning can solve most of the forearm fatigue problems; however, lack of dexterity and hand trauma remain critical issues. Additionally, significant improvements in glove design have occurred since Apollo, however they do not completely alleviate fatigue during longer EVAs (Scheuring et al. 2007).

The Apollo crews also reported that sloped terrain on the lunar surface caused fatigue. The crews remarked that stable footing was limited and leg fatigue would become more pronounced in terrain steeper than approximately 26°, although they estimated the exact angle of the slope. Lack of suit mobility, primarily at the hips, made getting in and out of steep terrain difficult (Scheuring et al. 2007).

Experience from Apollo also indicted that mental and physical rest plans should be introduced into extended Moon stays to allow adequate rest between lunar EVA. Apollo astronauts stated, “Consider mental and physical fatigue here separately. Although there was not a lot of physical fatigue [during the lunar activity], the mind was being used quite a bit. You can sometimes wear your brain out before your body is fatigued” (Scheuring et al. 2007).

IV.5. Mental State

IV.5.1. Situational Awareness

Operations tempo is driven by the scheduling of mission tasks, and can affect performance, workload, and situation awareness (SA) of crewmembers. The same amount of work can be more or less taxing on crew depending on other factors such as fatigue, deconditioning, stress and anxiety, or medical conditions. Low workload levels have been associated with boredom and decreased attention to task; whereas, high workload levels have been associated with increased error rates and the narrowing of attention to the possible detriment to tasks. In addition, when materials such as procedures, directions, checklists, graphic depictions, tables, charts, or other published guidance are misleading or unclear, workload is further impacted, and an unsafe situation results. The severity of the consequences increases with the duration of the mission (Sandor et al. 2013).

Current space flight crews rely on onboard automated systems. As increasing numbers of automated/robotic systems are designed to assist the human, a synergistic relationship must be developed that allows the human and automation to work together to successfully accomplish tasks. On future longer-duration missions with greater EVA demands and increased autonomy, crews will rely even more on these systems to provide information that is appropriate, accurate, and up-to-date. In addition, increased automation will require special emphasis on task design and additional training to ensure that the crew can perform the automated tasks in the event of automation failure. Automated tasks must be carefully designed to prevent the crew from losing SA, or becoming unaware or complacent about potential hazards. These situations could ultimately result in system errors, degraded crew performance, and compromised crew and vehicle safety (Sandor et al. 2013). Additionally, coordination of crewmember responsibility and decision making will be affected because the mission commander will likely be unable to manage all systems and personnel at a single time (Endsley 1995).

IV.5.2. Cognitive State

Research in the area of theoretical and applied psychology identifies that humans' physical, sensory, perceptual, and cognitive capabilities have constraints that are related to performance inefficiencies, including workload increases and operator error. In the area of cognitive capabilities, for example, the amount of information that can be processed by working memory is limited (Baddeley 1992; Miller 1956). Therefore, information overload can be a problem for an operator when they try to accomplish tasks that load their working memory. On the other hand, information underload can lead to decreased vigilance and loss of situation awareness, i.e., being less aware of important aspects of the environment needed for the current task and future actions. For all these reasons, human capabilities and limitations should be taken into consideration in the design of tasks and associated procedures, hardware, and software (Sandor et al. 2013).

Human capabilities and limitations can be affected greatly by the duration of a mission and the degree of subsequent deconditioning. Strength and aerobic power of load-bearing muscles can decrease during spaceflight missions. On-orbit exercise regimens have been implemented to counteract these deficits, but, to date, they have been only partially effective. Crewmembers are also affected by sleep loss and circadian desynchrony, which have been linked to cognitive and physical performance decrements (Whitmire et al. 2009). Overall, the long-term effects of living

in space and the effects on performance are still generally unknown. It is known that perception in every modality, reaction time, motor skills, and workload can be affected while in space, and thus affect performance (Legner 2004). Therefore, it is important to understand how tasks, procedures, and schedules may need to be modified as deconditioning occurs (Sandor et al. 2013).

More detailed background and evidence can be found in the NASA HRP “Evidence Report: Risk of Inadequate Critical Task Design” (Sandor et al. 2013).

IV.5.3. Psychological State

Stressful conditions are inherent to space missions. Working in space involves danger, isolation, and confinement; therefore, space is understood to be an extreme work environment. Survival in space requires constant shelter or protective gear, and it is also subject to equipment malfunctions. Crewmembers must adapt to a certain level of danger or threat to survive. They must also adapt to certain levels of isolation because contact with others (i.e., outside of the immediate crew) may be very limited and inconsistent at times, and isolation from family and friends may create social rifts and isolation that persist after flight. Finally, space flight crewmembers must adapt to being confined to a limited living and working space. Ground-based research in similar conditions (e.g., submarines, offshore oil rigs, polar stations) has found that such conditions are generally detrimental to psychological health and social well-being over prolonged periods (Braun and Sells 1962) (Britt and Bliese 2003) (Krueger 2001) (Schmidt et al. 2009).

Exploration space missions could require crews and ground operations to operate more or less autonomously because the degree of crew isolation increases with the distance that the spacecraft travels from the Earth. Crews are likely to have some periods of complete control as well as some periods of limited control over what tasks are done, how the tasks are done, and when they are done. Ground operations are likely to stipulate total control at certain points in the mission, and unable to provide any control during other parts of the mission. Shifts in operational autonomy are expected to impact psychosocial adaptation to space flight demands (Kanas and Manzey 2008). It is important to understand how these factors (i.e., isolation, physical space, individual and group autonomy, etc.) influence psychosocial adaptation among crewmembers, as these factors ultimately will impact crew performance (Langfred 2000) (Schmidt et al. 2009).

More detailed background and evidence can be found in the NASA HRP Evidence Book: “Risk of Performance and Behavioral Health Decrements Due to Inadequate Cooperation, Coordination, Communication, and Psychosocial Adaptation within a Team” (Landon 2016).

V. COMPUTER-BASED MODELING AND SIMULATION

V.1. Life Sciences Implications of EVA

In 2010, an effort was undertaken to document preliminary, predicted, human health and performance implications of expected operational concepts for lunar surface EVA (Chappell et al. 2010b). Algorithms developed through simulation and testing in lunar analog environments were used to predict crew metabolic rates and ground reaction forces experienced during lunar

EVA. Subsequently, total metabolic energy consumption, daily bone load stimulus, total oxygen needed, and other variables were calculated and provided to Human Research Program and Exploration Systems Mission Directorate stakeholders. To provide context to the modeling, the report included an overview of some lunar surface scenarios that were under consideration as part of NASA's Constellation Program. Concise descriptions of the contributing analog testing and development of the algorithms were also provided.

The effort undertaken to model the life sciences implications of lunar EVA can be extended to remain current with evolving exploration destinations, assumptions, and concepts, and to provide additional data and analyses collected during ongoing analog research and integrated testing results.

V.1.1.1. EVA Timeline Analysis and Computational Modeling

Modeling was performed using timelines from DRATS 2009 (Abercromby and Gernhardt Manuscript submitted for publication) and a reasonable estimation of a typical EVA on a planetary surface. Data from field tests were combined with physiological and performance data collected during the Integrated Suit Tests to project some of the physiological implications associated with these lunar surface operations (Chappell et al. 2010b). A model was developed that takes into account such variables as subject mass, suit mass, suit pressure, gravity level, ambulation speed, ambulation distance, ground reaction forces, exploration task type, and time spent performing each exploration task. The model then outputs information such as metabolic energy consumed, oxygen used, water used, and accumulated load/bone stimulus. The analysis has been used to guide planning for other research plan development as in Fig. 11, which shows an overview of the process used to produce the simulation to be undertaken as part of a future exploration atmospheres validation study.

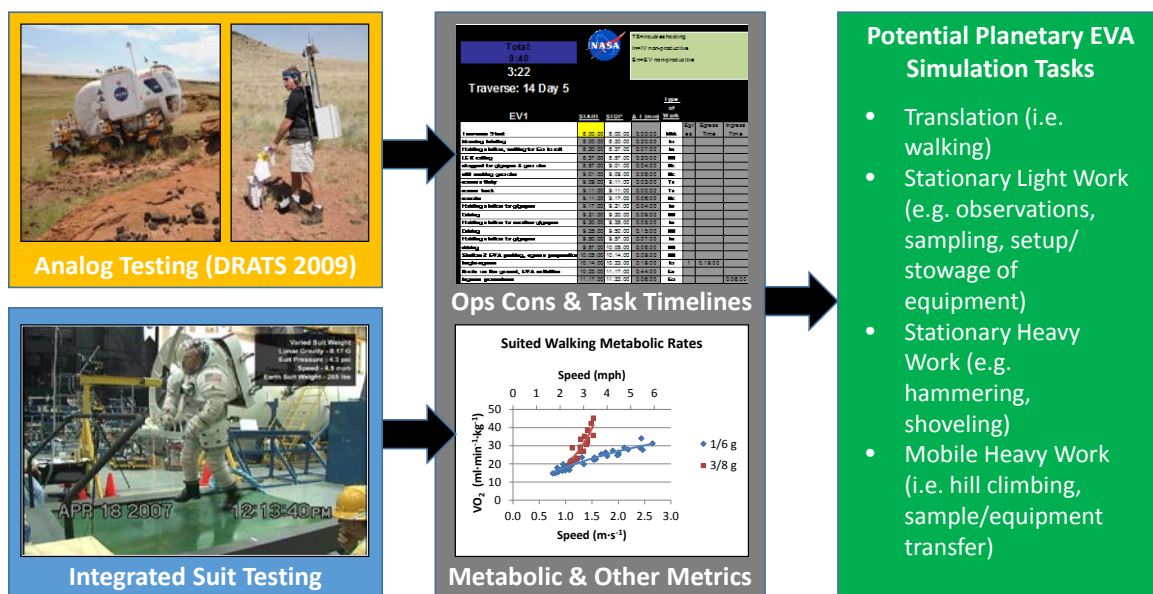


Fig. 11. Process used to produce the proposed planetary EVA simulation for an exploration atmospheres validation study.

The proposed split of EVA times and activity proposed for the exploration atmospheres validation study will be based on that observed in DRATS 2009, during which there were on average 4 EVAs per day, each of 45 minutes duration. The split of activities observed during DRATS 2009 is shown in Fig. 12.

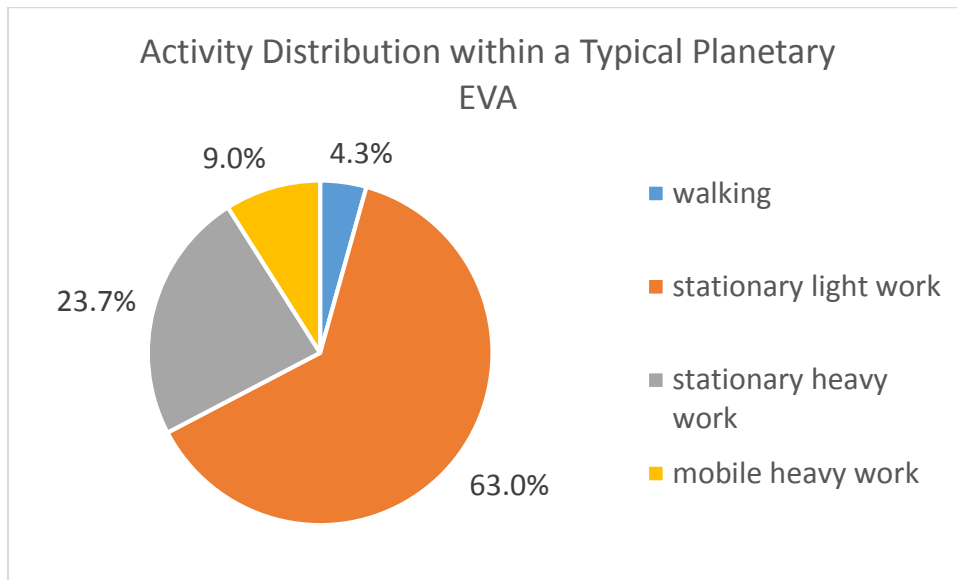


Fig. 12. The activity distribution with a typical planetary EVA is shown and based on that which was observed during DRATS 2009.

To estimate the amount of exercise achieved related to EVA tasks, data from the Integrated Suit Tests (Abercromby *et al.* 2010) and field tests will be used to predict the metabolic rate during exploration activities. For metabolic rates during the different activities (Fig. 12), measured rates from IST-1 and IST-2 will be used and correlated with tasks according to whether the tasks are mostly stationary or not, and whether they required light or heavy work. The specific methods and equipment that can be adapted to work within the altitude chamber will be formulated, developed, tested, and verified in the first part of the study before testing begins on subjects.

This use of EVA timeline analysis, results from prior testing, and modeling provides an integrated approach to test planning and execution of EVAs with the results iteratively informing follow-on testing.

VI. RISK IN CONTEXT OF EXPLORATION MISSION OPERATIONAL SCENARIOS

EVA is a critical factor in the success of the construction, maintenance, scientific, and exploration aspects of every exploration architecture concept being considered by NASA. Some concepts of operation call for each crewmember to perform up to 24 hours of EVA per week for missions lasting up to 6 months. This corresponds to as many as 624 hours of EVA per crew member in a single mission. As described in this evidence report, the risks associated with any

inadequacies that exist in current EVA systems – particularly with respect to suit-induced trauma – will be greatly amplified by such frequent EVAs.

Planetary mission architectures include small pressurized rovers (SPRs) as a core element of the surface mobility system. The implications of SPRs on crew health, safety, productivity, and efficiency are potentially enormous. The availability of a pressurized safe-haven that provides DCS treatment, solar particle event (SPE) protection, and on-site injury treatment, and can be reached within 20 minutes at all times, would significantly reduce many of the risks associated with planetary exploration. Furthermore, because crewmembers would travel the planetary surface inside the SPRs, this would reduce the overall number of in-suit EVA hours to achieve the same (or greater) science/exploration return. The possibility of performing single-person EVAs with a second crewmember inside the SPR would further reduce total EVA hours. In addition, the number of cycles on the EVA suits would be decreased, thereby increasing the life of each EVA suit and reducing hardware failure risk for crewmembers.

VII. GAPS

In the following table, the current defined gaps associated with this risk are listed along with associated metrics that will help to determine gap closure.

Gap #		HRP EVA Risk Gap	Metric
Old	1-5	Original Gaps	Restructured into Gaps 6-13 in 2009
EVA Crew, Systems, Environments, & Tasks	6	What crew physiological & performance capabilities ¹ are required for EVA operations ² in exploration environments ³ ?	A. Minimum aerobic fitness standard on performance during suited operations standard defined.
			B. Muscle strength and power required for performance during suited operations understood and minimum standards defined
			C. Anthropometry (baseline as well as in-flight changes) effect on human performance during suited operations defined
			D. Losses in physiological function and EVA preparation during transit to exploration destinations understood
			E. Degree that surface EVA activities serve as a physiological countermeasures understood
	7	How do EVA suit system design parameters ⁴ affect crew health and performance in exploration environments?	A. CG location effect on suited performance in exploration environments defined
			B. Joint characteristics (ROM, location, torque, hard vs soft) and overall mobility effects on performance in exploration environments understood
			C. Suit mass effect on performance in exploration environments understood
			D. Suit pressure effect on performance in exploration environments understood
			E. Suit design parameter changes on human health and performance model completed
	7B	How does suit sizing and fit affect crew health and performance in the exploration environments?	A. Objective measure(s) of suit fit defined
			B. Suit sizing and fit model developed and validated
	8	What are the physiological inputs and outputs associated	A. Metabolic cost required to perform EVA operations ² in exploration

Gap #	HRP EVA Risk Gap	Metric
	with EVA operations ² in exploration environments ³ ?	environments ³ defined
		B. Nutrition and hydration needs during suited operations defined
		C. In-suit heat and moisture effects on crew health & performance understood
		D. Excess levels of in-suit CO ₂ effects on crew health & performance understood
		E. Reduced gravity effects on crew physiological and functional performance during EVA tasks defined
		F. Variation of terrain (e.g. slope angle, surface hardness, surface variation) effects on crew physiological and functional performance during EVA tasks defined
	9	A. Task design (i.e. EVA equipment & methods) effects on crew health and performance understood
		B. Objective measures of fatigue related to EVA suited operations defined
		C. EVA duration and frequency (e.g. 8x1 hr, 4x2hr, 2x4 hr 1x8 hr EVA frequency x duration) effects on crew performance and health understood
	10	A. Physiological and EVA system parameters that must be monitored, displayed, alerted, and/or sent to the ground to enable safe and effective suited operations are defined
		B. Effective methods for provision of real-time knowledge of physiological and EVA system parameters to the EVA crew member understood
		C. Effective methods for real-time physiological and EVA system parameters utilization with biofeedback systems to improve EVA crew health, performance and autonomy are understood
Injury	11	A. Mechanisms or tasks that lead to acute, chronic, cumulative, or repetitive suit-induced injury are tracked and understood
		B. Glove design parameters that impact

Gap #		HRP EVA Risk Gap	Metric
		mitigated?	crew performance and safety defined
			C. Technologies or countermeasures developed to reduce the likelihood of suit-induced trauma
			D. Suit-related trauma monitoring, logging, and treatment tracking
			E. Techniques and technologies developed to treat, stabilize, monitor, and transport incapacitated suited crew in exploration environments
Environmental	12	What is the risk of decompression sickness?	Moved from an EVA Gap to a standalone risk in 2010. See DCS Risk Evidence Report (Conkin et al. 2016).
	13	What is the risk of hypoxia during exploration missions?	Moved from an EVA Gap to a standalone risk in 2014. See Hypoxia Risk Evidence Report (Norcross et al. 2015).
Integration	14	What other EVA-related risks, developments and technologies exist that may affect EVA research?	Gap to be closed due to the development of the Integrated EVA Human Research Plan (Abercromby et al. 2016) and a Customer Supplier Agreement between several of the EVA focused organizations at JSC.
¹ e.g. anthropometry, aerobic fitness, muscle strength & power			
² acceptable functional performance of expected nominal and contingency suited tasks			
³ i.e. Moon, NEA, Mars, L2 and other deep space microgravity locations			
⁴ (e.g. CG, mass, pressure, mobility, joint characteristics, suit fit; includes suit, PLSS, and other enabling equipment)			

VIII. CONCLUSION

Future human space exploration missions will be more dependent on EVA excursions away from a pressurized habitat or vehicle than any program in the history of NASA. EVA will be required to conduct planned scientific expeditions, assemble structures, perform nominal maintenance, and intervene and solve problems outside of the vehicle that cannot be solved either robotically or remotely. The ultimate success of future exploration missions is dependent on the ability to perform EVA tasks efficiently and safely in these challenging environments.

To date, our direct understanding of human health and performance parameters in partial-gravity environments is limited to observations of, and lessons learned from, Apollo-era astronauts who performed EVAs on the lunar surface. Since the Apollo Program, and using lessons learned from microgravity EVAs aboard the Space Shuttle and ISS, new prototype suits have been in development for future space exploration activities. However, to date there has been limited quantification of the physiological and biomechanical variables associated with suited activities in micro and partial gravity. An integrated EVA testing research plan is required to better characterize the impacts to crew health and performance of the various parameters that are involved in EVA operations.

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X. TEAM

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XI. LIST OF ACRONYMS

ARGOS – Active Response Gravity Offload System
BME – biomedical engineer
CG – center of gravity
CHAPS – contingency hypobaric astronaut protective suit
COM – center of mass
CTSD – Crew and Thermal Systems Division
DCS – decompression sickness
DOF – degrees of freedom
EMU – extravehicular mobility unit
EAMD – Exploration Analogs and Mission Development
ECS – Environmental Control System
EPSP – EVA Physiology, Systems, and Performance
ESPO – EVA Systems Project Office
EVA – extravehicular activity
EWT – EVA Walkback Test
FIU – Florida International University
FTT- functional task testing
GCPS – gravity compensation and performance scale
GRF – ground reaction force
HRP – Human Research Program
HUT – hard upper torso
IDB – in-suit drink bag
ISS – International Space Station
IST – integrated suit test
IVA – intravehicular activity
JSC – Johnson Space Center
LCG – liquid cooling garment
MACES – modified advanced crew escape suit
MAG – maximum absorbency garment
MOD – Mission Operations Directorate
NASA – National Aeronautics and Space Administration
NBL – Neutral Buoyancy Lab
NEA – near Earth asteroid
NEEMO – NASA Extreme Environment Mission Operations
PB – prebreathe
PLSS – portable life support system
POGO – Partial gravity simulator
RATS – research and technology studies
RGO – Reduced Gravity Office
RPE – rating of perceived exertion
SA – situational awareness
SCUBA – self-contained underwater breathing apparatus
SD – standard deviation
SPE – solar particle event
SPR – small pressurized rovers

SVMF – Space Vehicle Mockup Facility

U.S. – United States

VGE – venous gas emboli

WEI – work efficiency index

XII. APPENDIX A: EVA GAPS AND MASTER LOGIC DIAGRAM CONTRIBUTING FACTORS MAPPING

Table 2 - Gap to Contributing Factor Mapping, Gaps 6, 7, 8, 9

Gap #	Gap	Metric	Contributing Factors																							
			Suit Habitability					In-Suit Physical Environment					EVA Factors					Physical State		Mental State						
			EVA Suit Design	EVA Suit Fit	EVA Glove Function	Waste Management	Nutrition and Hydration	Hypoxia	Hypercapnia	Internal Suit Pressure	Hyper/Hypothermia	Humidity	Excessive Radiation Exposure	Work Efficiency Index	EVA Task & Timeline Design	EVA Resources	EVA Environment (Terrain, Gravity, Dust)	Quality of EVA Procedures	EVA Training	EVA Crew Collaboration	Crewmember Physical Preparation	Pre-Existing Injury or Illness	Fatigue	Situational Awareness	Cognitive State (Knowledge, Attention)	Psychological State (Stress, Morale)
6	What crew physiological & performance capabilities ¹ are required for EVA operations ² in exploration environments ³ ?	A. Minimum aerobic fitness standard on performance during suited operations standard defined.	x	x										x	x					x						
		B. Muscle strength and power required for performance during suited operations understood and minumum standards defined	x	x	x										x	x					x					
		C. Anthropometry (baseline as well as in-flight changes) affect on human performance during suited operations defined	x	x											x	x										
		D. Losses in physiological function and EVA preparation during transit to exploration destinations understood														x		x		x						
		E. Degree that surface EVA activities serve as a physiological countermeasures understood	x												x	x										
7	How do EVA suit system design parameters ⁴ affect crew health and performance in exploration environments?	A. CG location affect on suited performance in exploration environments defined	x	x										x	x					x		x				
		B. Joint characteristics (ROM, location, torque, hard vs soft) and overall mobility affects on performance in exploration environments understood	x	x					x						x	x					x		x			
		C. Suit mass affect on performance in exploration environments understood	x	x											x	x					x		x			
		D. Suit pressure affect on performance in exploration environments understood	x	x					x						x	x					x		x			
		E. Suit design parameter changes on human health and performance model completed	x	x					x						x	x	x				x		x			
		F. Objective measure(s) of suit fit defined	x	x																						
8	What are the physiological inputs and outputs associated with EVA operations ² in exploration environments ³ ?	A. Metabolic cost required to perform EVA operations ² in exploration environments ³	x	x				x		x					x	x					x					
		B. Nutrition and hydration needs during suited operations defined	x	x			x								x	x	x					x				
		C. In-suit heat and moisture effects on crew health & performance understood	x							x	x	x			x	x					x					
		D. Excess levels of in-suit CO ₂ effects on crew health & performance understood	x							x	x				x	x										
		E. Reduced gravity effects on crew physiological and functional performance during EVA	x	x	x					x					x	x	x					x		x		
		F. Variation of terrain (e.g. slope angle, surface hardness, surface variation) effects on	x	x						x					x	x						x		x		
9	What is the effect on crew performance & health of variations in EVA task design and operations concepts for exploration environments ³ ?	A. Task design (i.e. EVA equipment & methods) effects on crew health and performance understood	x	x	x									x	x	x	x	x	x							
		B. Objective measures of fatigue related to EVA suited operations defined	x												x	x							x			
		C. EVA duration and frequency (e.g. 8x1 hr, 4x2hr, 2x4 hr 1x8 hr EVA frequency x duration) effects on crew performance and health understood	x	x	x	x	x								x	x	x	x	x	x	x	x	x	x	x	x
¹ e.g. anthropometry, aerobic fitness, muscle strength & power																										
² acceptable functional performance of expected nominal and contingency suited tasks																										
³ i.e. Moon, NEA, Mars, L2 and other deep space microgravity locations																										
⁴ (e.g. CG, mass, pressure, mobility, joint characteristics, suit fit; includes suit, PLSS, and other enabling equipment)																										

Table 3 - Gap to Contributing Factor Mapping, Gaps 10, 11, 14

			Contributing Factors																									
			Suit Habitability				In-Suit Physical Environment				EVA Factors						Physical State		Mental State									
Gap #	Gap	Metric	EVA Suit Design	EVA Suit Fit	EVA Glove Function	Waste Management	Nutrition and Hydration	Hypoxia	Hypercapnia	Internal Suit Pressure	Hyper/Hypothermia	Humidity	Excessive Radiation Exposure	Work Efficiency Index	EVA Task & Timeline Design	EVA Resources	EVA Environment (Terrain, Gravity, Dust)	Quality of EVA Procedures	EVA Training	EVA Crew Collaboration	Crewmember Physical Preparation	Pre-Existing Injury or Illness	Fatigue	Situational Awareness	Cognitive State (Knowledge, Attention)	Psychological State (Stress, Morale)		
10	Can knowledge and use of real-time physiological and system parameters during EVA operations improve crew health and performance?	A. Physiological and EVA system parameters that must be monitored, displayed, alerted, and/or sent to the ground to enable safe and effective suited operations are defined	x												x	x	x								x	x		
		B. Effective methods for provision of real-time knowledge of physiological and EVA system parameters to the EVA crew member understood	x													x	x	x								x	x	
		C. Effective methods for real-time physiological and EVA system parameters utilization with biofeedback systems to improve EVA crew health, performance and autonomy are understood	x													x	x	x								x	x	x
11	How do EVA operations ² in exploration environments ³ increase the risk of crew injury and how can the risk be mitigated?	A. Mechanisms or tasks that lead to acute, chronic, cumulative, or repetitive suit-induced injury are tracked and understood	x	x	x									x	x		x					x	x					
		B. Glove design parameters that impact crew performance and safety defined	x		x					x					x		x					x						
		C. Technologies or countermeasures developed to reduce the likelihood of suit-induced trauma	x	x											x		x		x			x						
		D. Suit-related trauma monitoring, logging, and treatment tracking																		x			x					
		E. Techniques and technologies developed to treat, stabilize, monitor, and transport incapacitated suited crew in exploration environments	x													x	x	x		x	x							
14	What other EVA-related risks, developments and technologies exist that may affect EVA research?	A. Monitoring and/or involvement in other HRP risk activities and developments that are ongoing or planned that may affect the EVA risk and/or research portfolio																										
		B. Monitoring and/or involvement in EVA-related hardware developments outside of HRP that are ongoing or planned and may affect the EVA risk and/or research portfolio																										
		C. Monitoring and/or involvement in EVA-related mission/architecture development outside of HRP that may affect the EVA risk and/or research portfolio																										
		¹ e.g. anthropometry, aerobic fitness, muscle strength & power																										
		² acceptable functional performance of expected nominal and contingency suited tasks																										
		³ i.e. Moon, NEA, Mars, L2 and other deep space microgravity locations																										
		⁴ (e.g. CG, mass, pressure, mobility, joint characteristics, suit fit; includes suit, PLSS, and other enabling equipment)																										